Dark Matter - How we are hunting the unknown

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Arthur B. McDonald Canadian Astroparticle Physics Research Institute

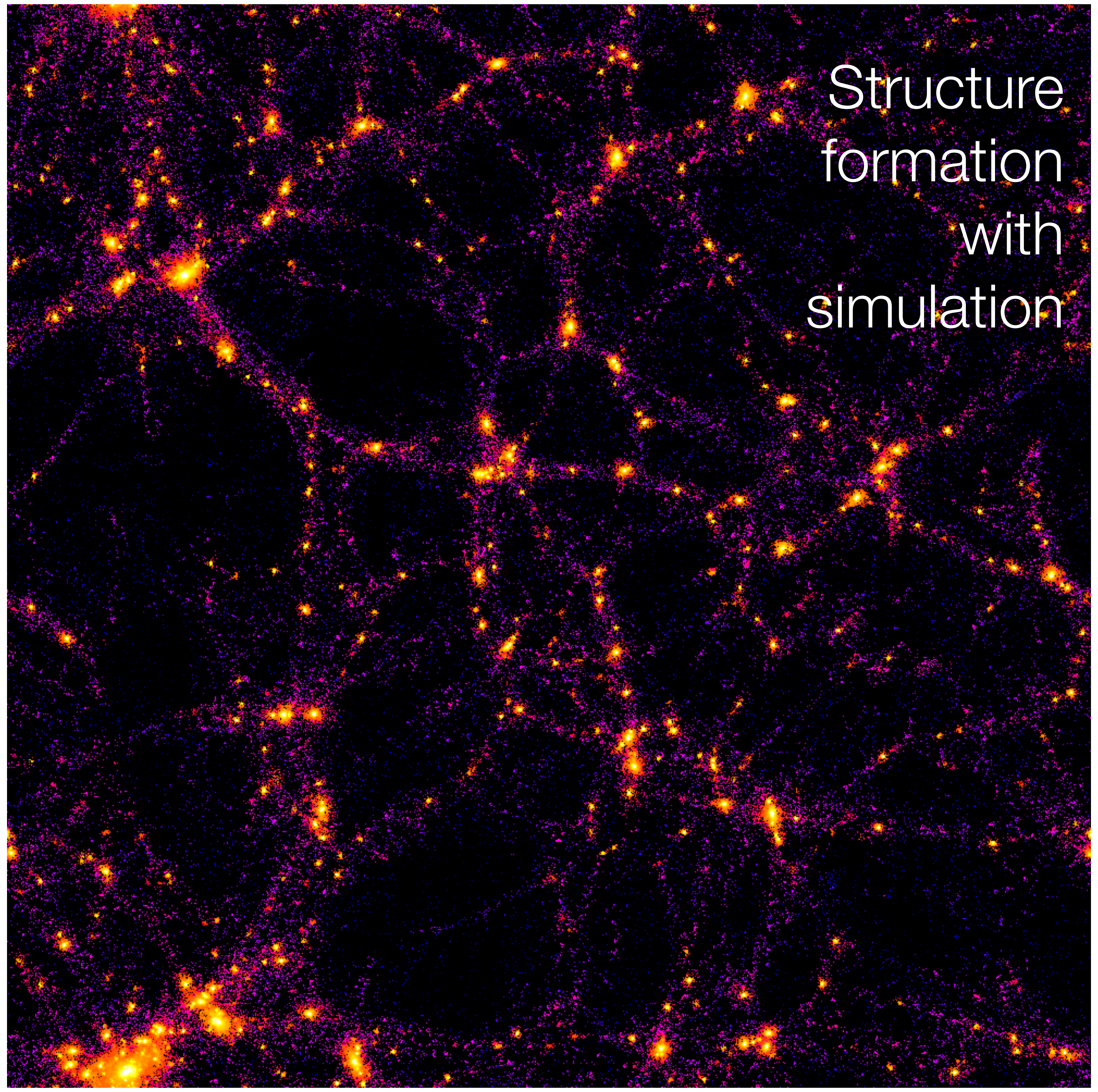
TRIUMF

Queen's University

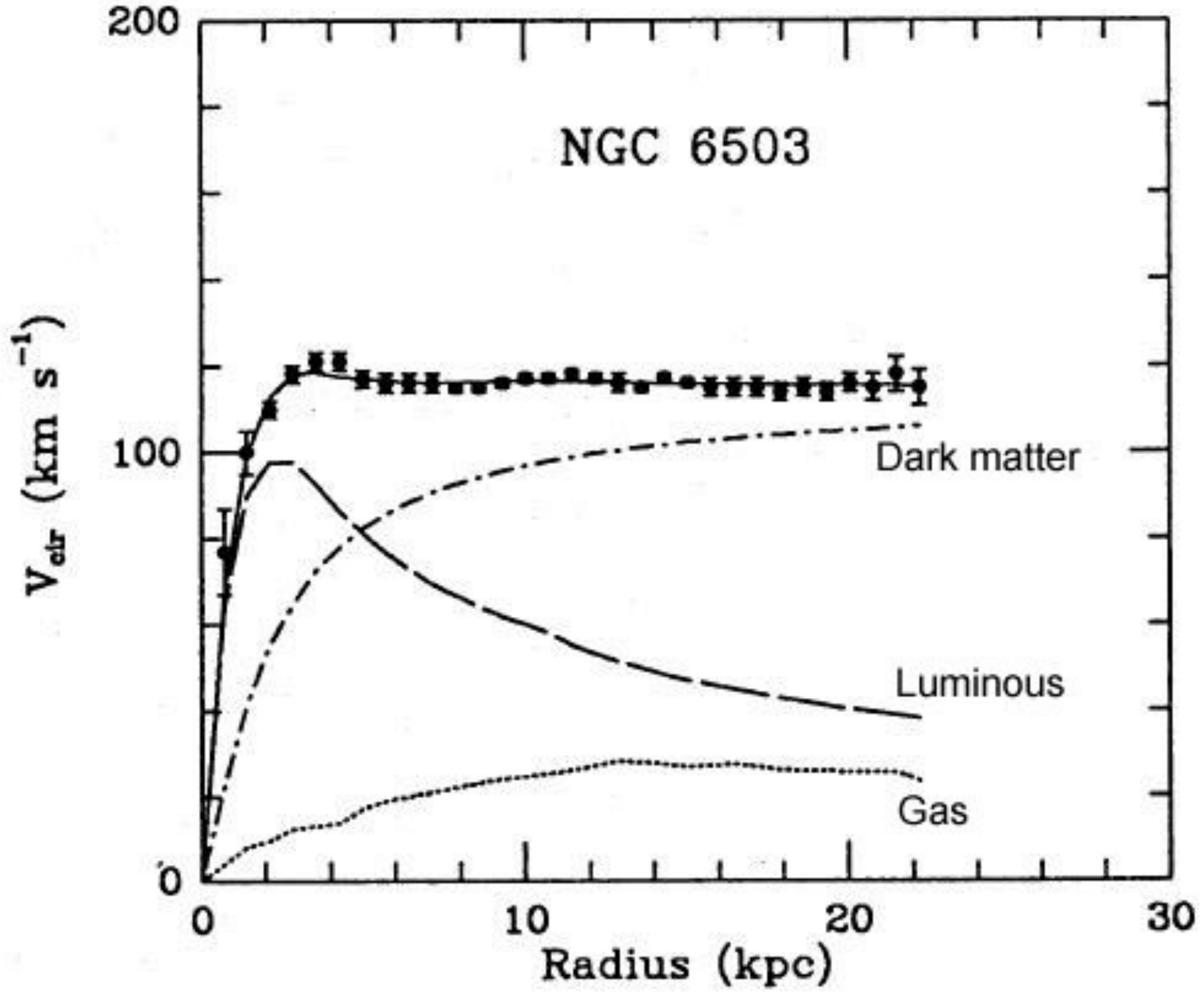
This talk

- This talk is a very abbreviated tour through experiments searching for dark matter
- Details are intentionally minimal, and attempts will be made not to dwell on the coolness of this stuff
- Also, biases will probably become obvious…

Dark Matter Evidence

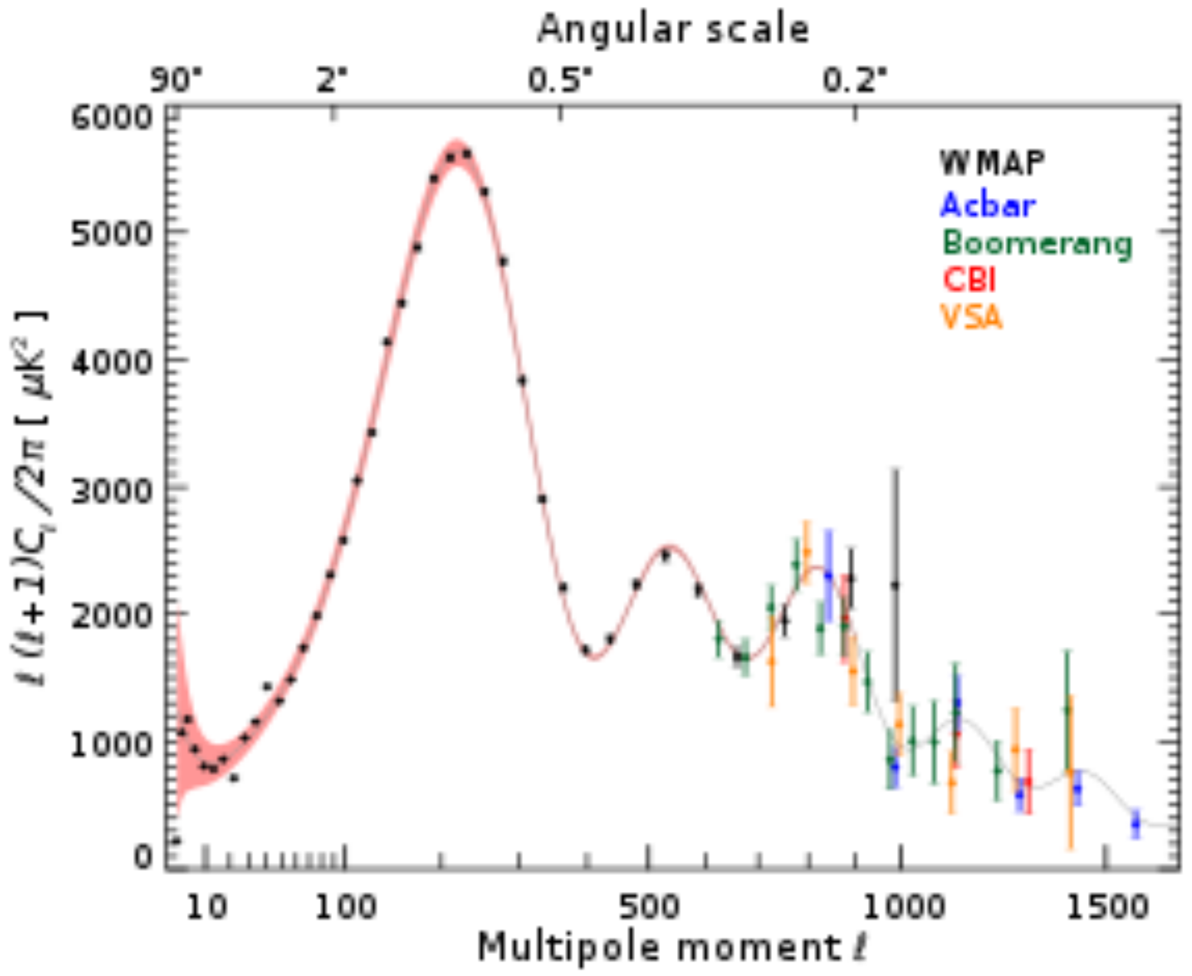


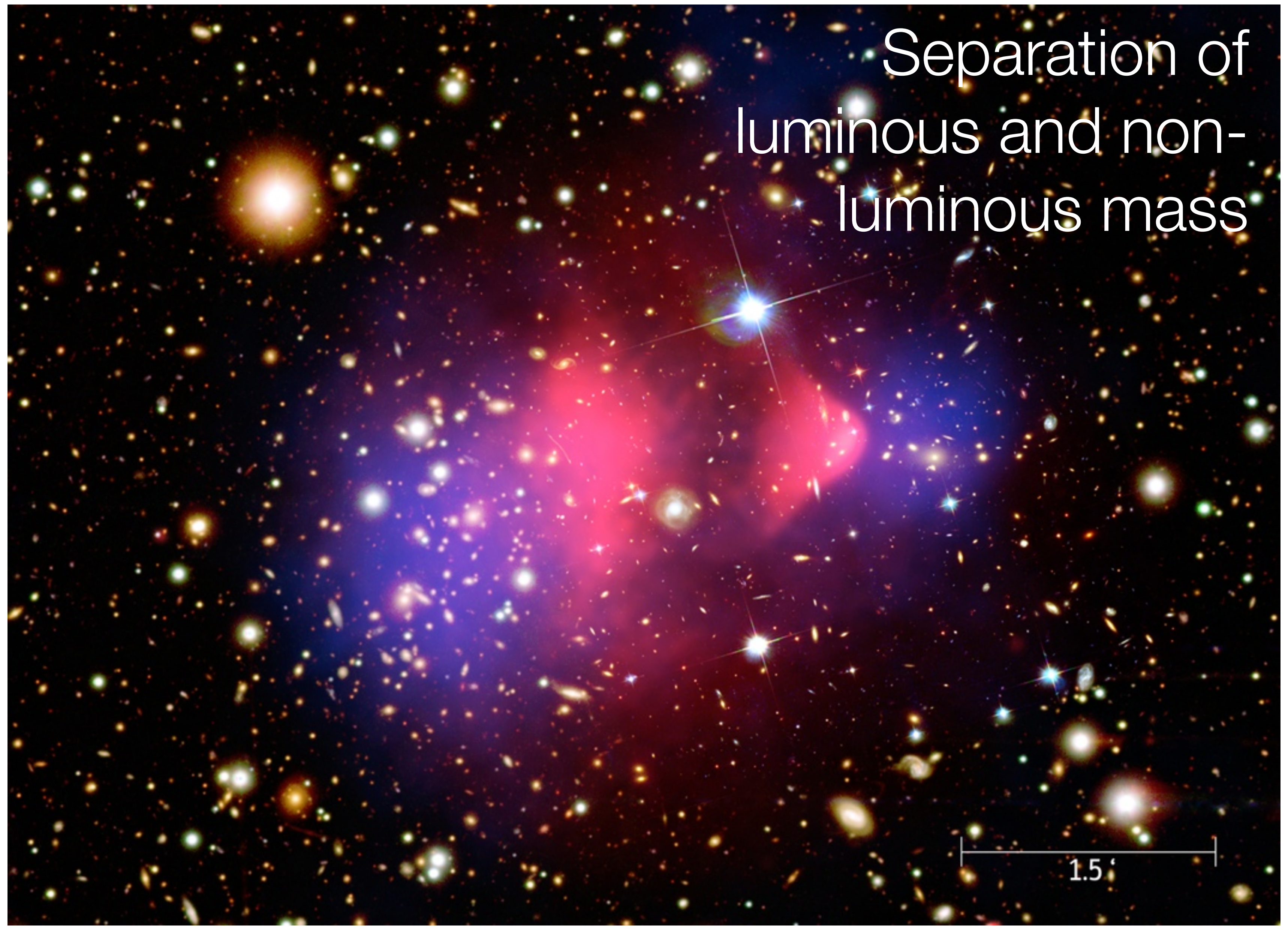
Already
“detected”
now in the era
of
“identification”



Galaxy
rotation
curves

Cosmic
microwave
background





Dark Matter: What Do We Know?

1. Long lived (survived until current day)
2. Non-baryonic (Hydrogen:Deuterium Ratio)
3. No EM interactions (haven't seen it)
4. 80% of all matter (rotation curves, CMB)
5. Non-relativistic (galactic structure formation, rotation curves)

Dark Matter: What Don’t We Know?

1. What is the fundamental nature of the dark matter? (Associated: what are its properties)
2. How was dark matter formed in the universe?
3. Does dark matter interact non-gravitationally with standard model particles?
4. Does dark matter interact non-gravitationally with itself?

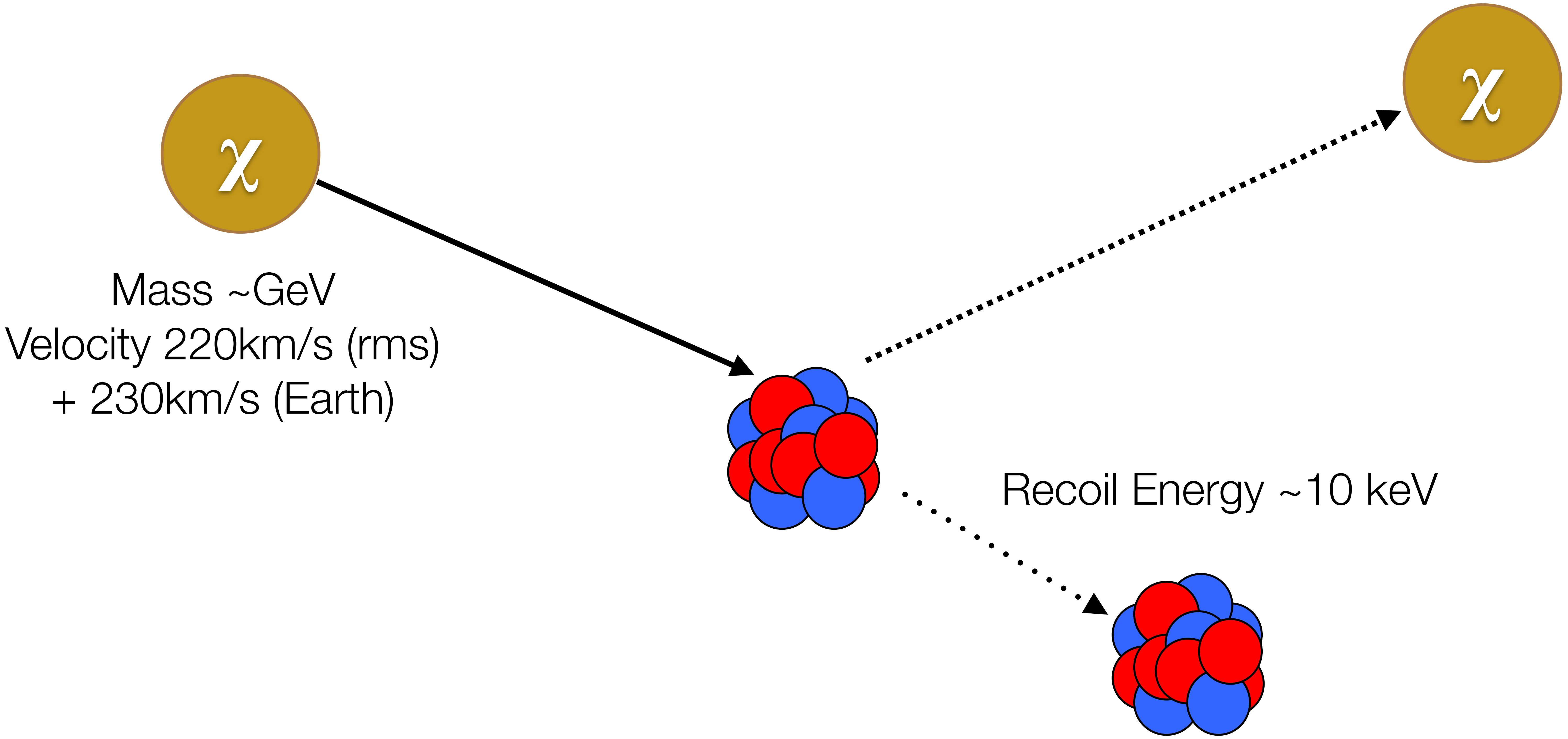
What could it be?

Nature **562** 51-56 (2018)

- Lots of potential solutions to the dark matter puzzle
- This talk focuses on WIMPs for several reasons…
  - Canadian thrust
  - Projects with which I've been involved

How are we chasing it?

- Exploiting its properties
- Dark matter exists - can collide elastically



How are we chasing it?

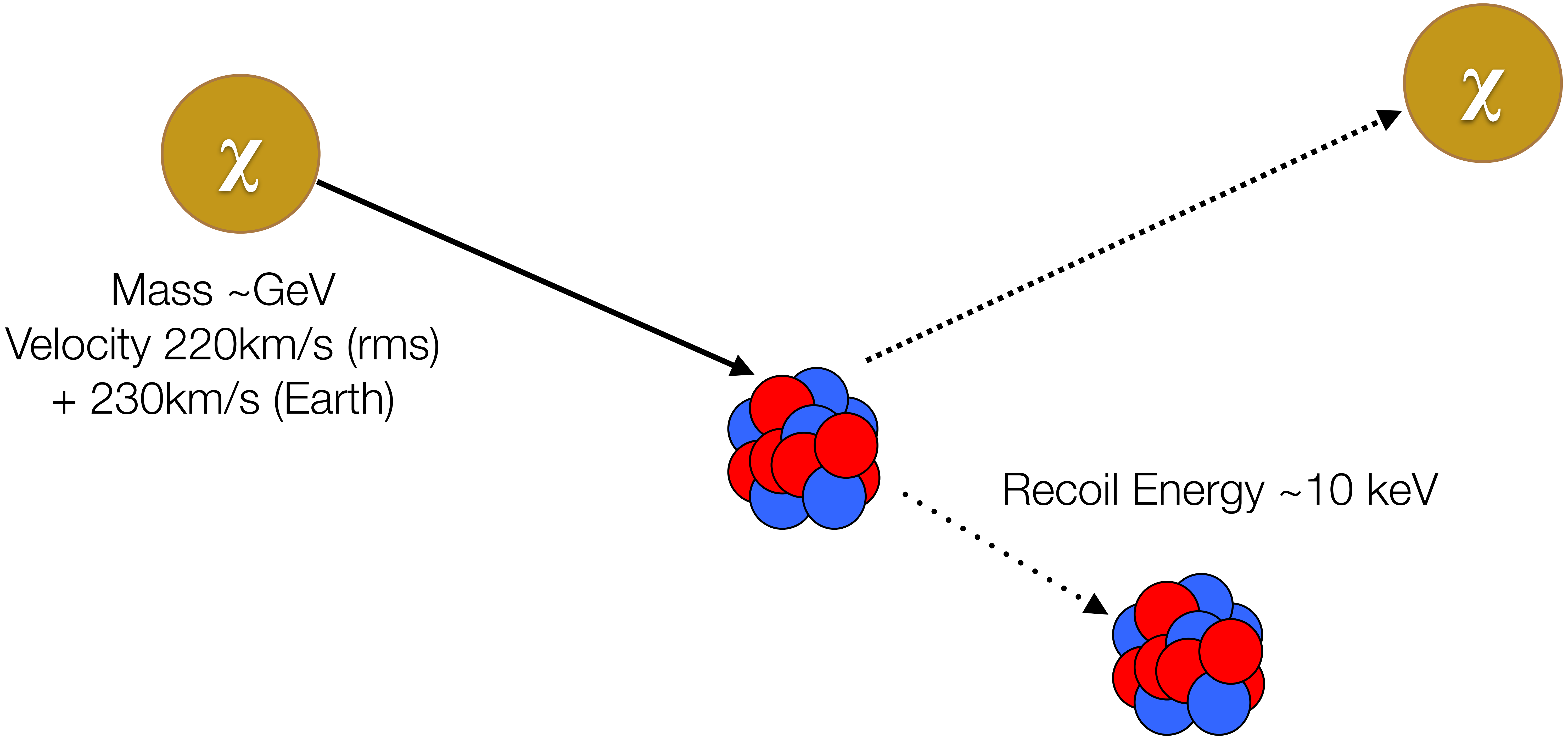
- Exploiting its properties
- Dark matter exists - can collide elastically

Aside 1: Energy scale of recoil

- 10 keV is very little energy
- A mosquito flying at full speed has about 1 TeV of energy (1×10^9 keV)

How are we chasing it?

- Exploiting its properties
- Dark matter exists - can collide elastically



One additional issue…

- Very rare interaction (usually <1 event per year per kilogram of target)
- Other events much more frequent

Detector Criteria

1. Sensitive to very small deposits of energy
2. Some way to differentiate how that energy is deposited (separate non-nuclear recoils)
3. (Clear path to sizing up to the tonne scale)

<1 event/kg/year

- need to have many 10s of years
- need to have many kg

Detector Criteria

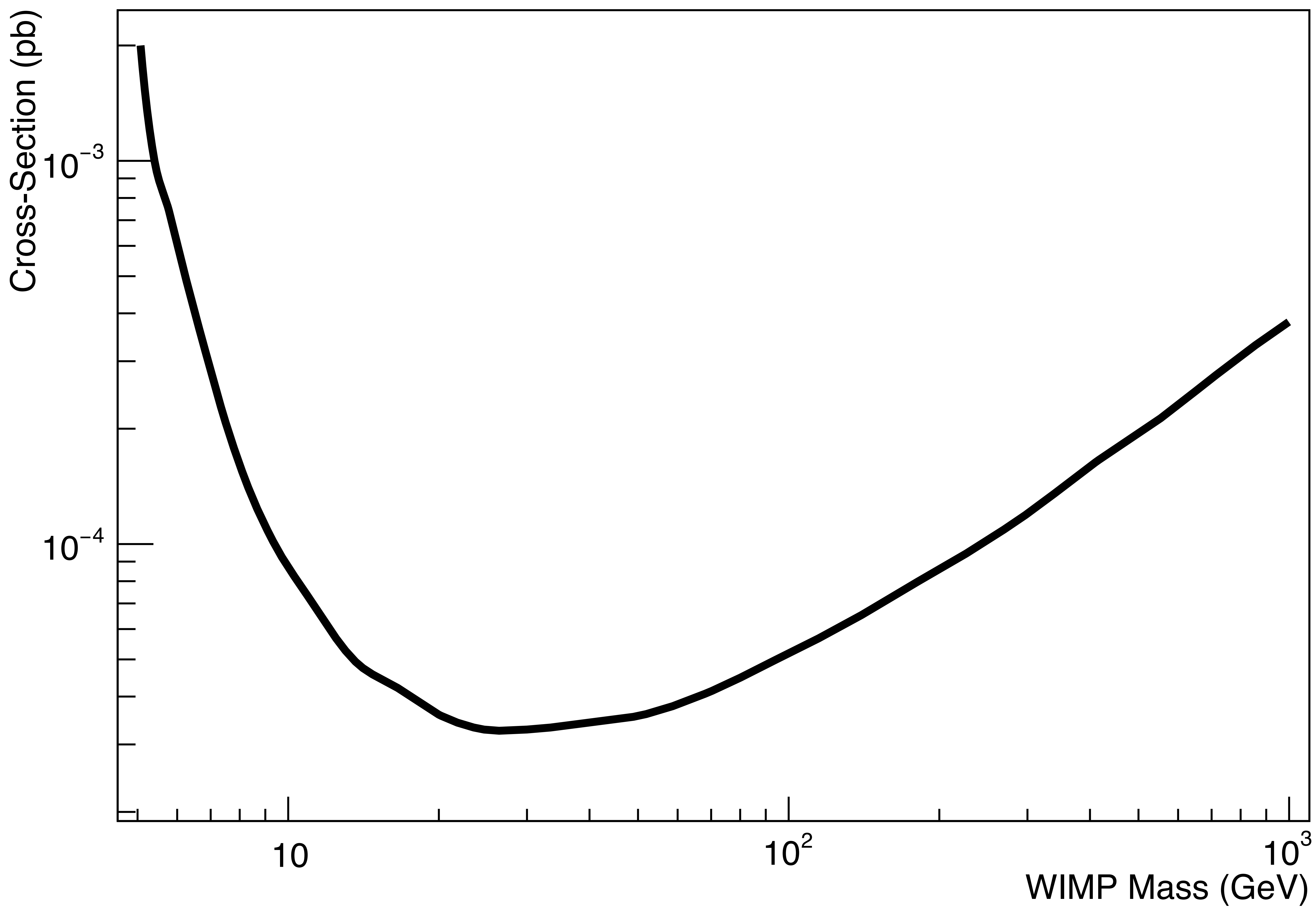
1. Sensitive to very small deposits of energy
2. Some way to differentiate how that energy is deposited (separate non-nuclear recoils)
3. (Clear path to sizing up to the tonne scale)
4. Want to compare the results with other experiments

<1 event/kg/year

- need to have many 10s of years
- need to have many kg

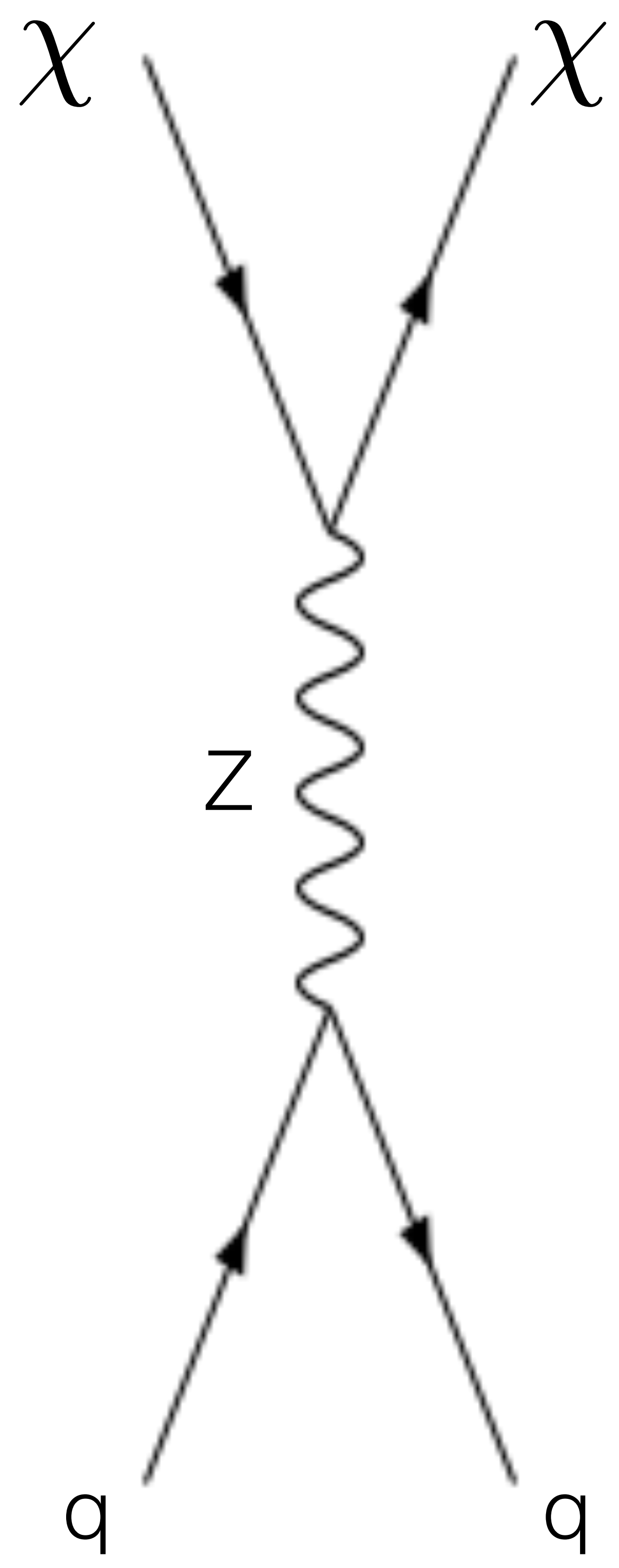
Experiment Competition

- Need a transferrable way to compare the performance of experiments
- Look at what combination of mass and cross-section they could discover



Experiment Competition

One fairly major complexity with the comparisons



Spin-Dependent

Coupling proportional to expectation value of nucleon spins and total nuclear spin

Favours nuclei with unpaired nucleons such as ^{19}F, ^{23}Na, ^{73}Ge

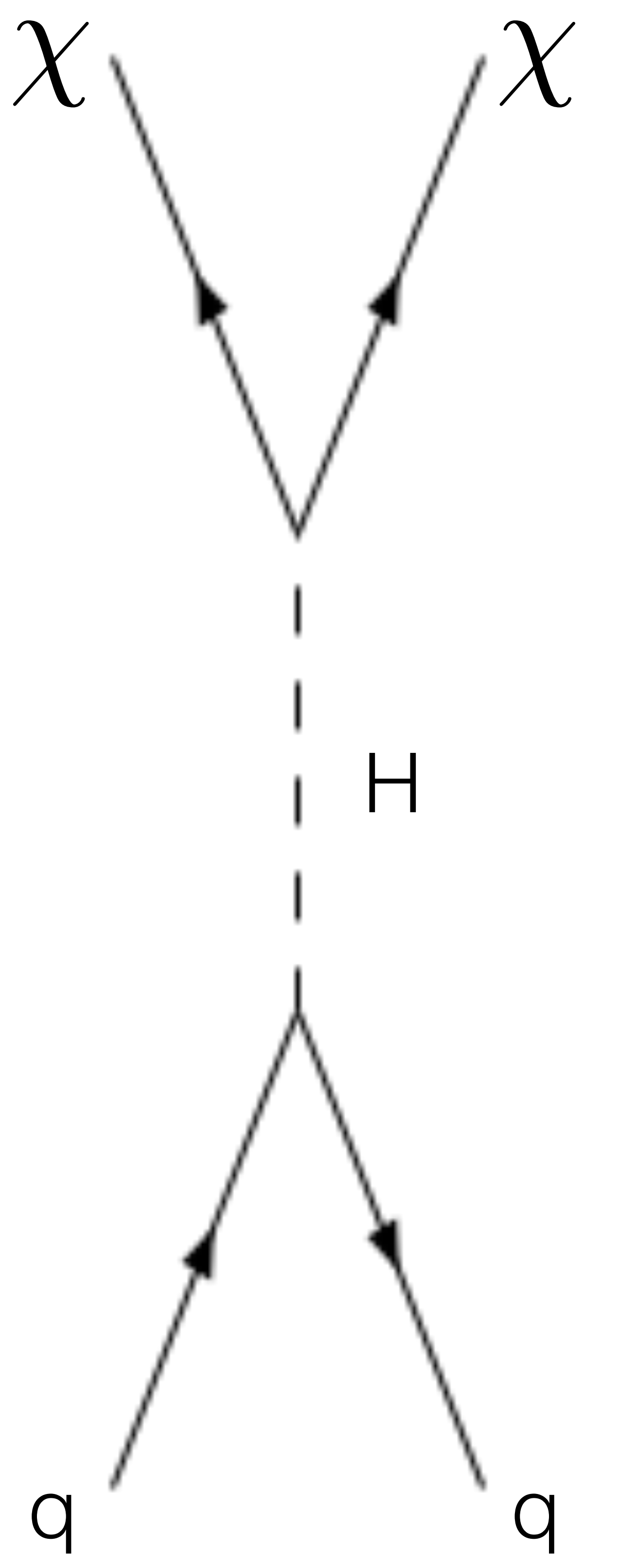
$$C_{spin} = \frac{8}{\pi}\frac{J+1}{J}\left[a_p < S_p > + a_n < S_n >\right]^2$$

Spin-Independent

Coupling proportional to the square of the atomic mass number

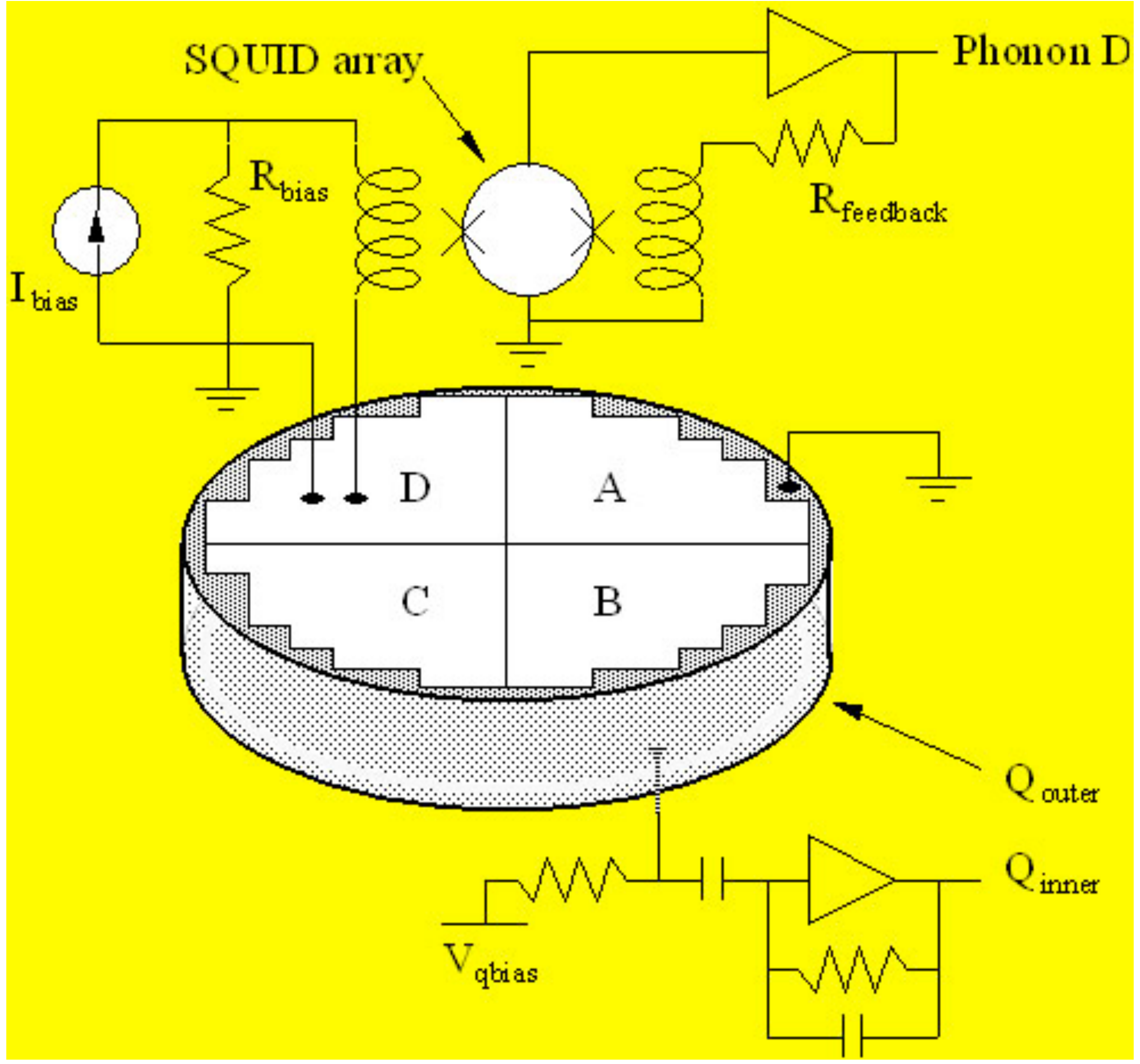
Favours heavy nuclei such as Ge, Xe

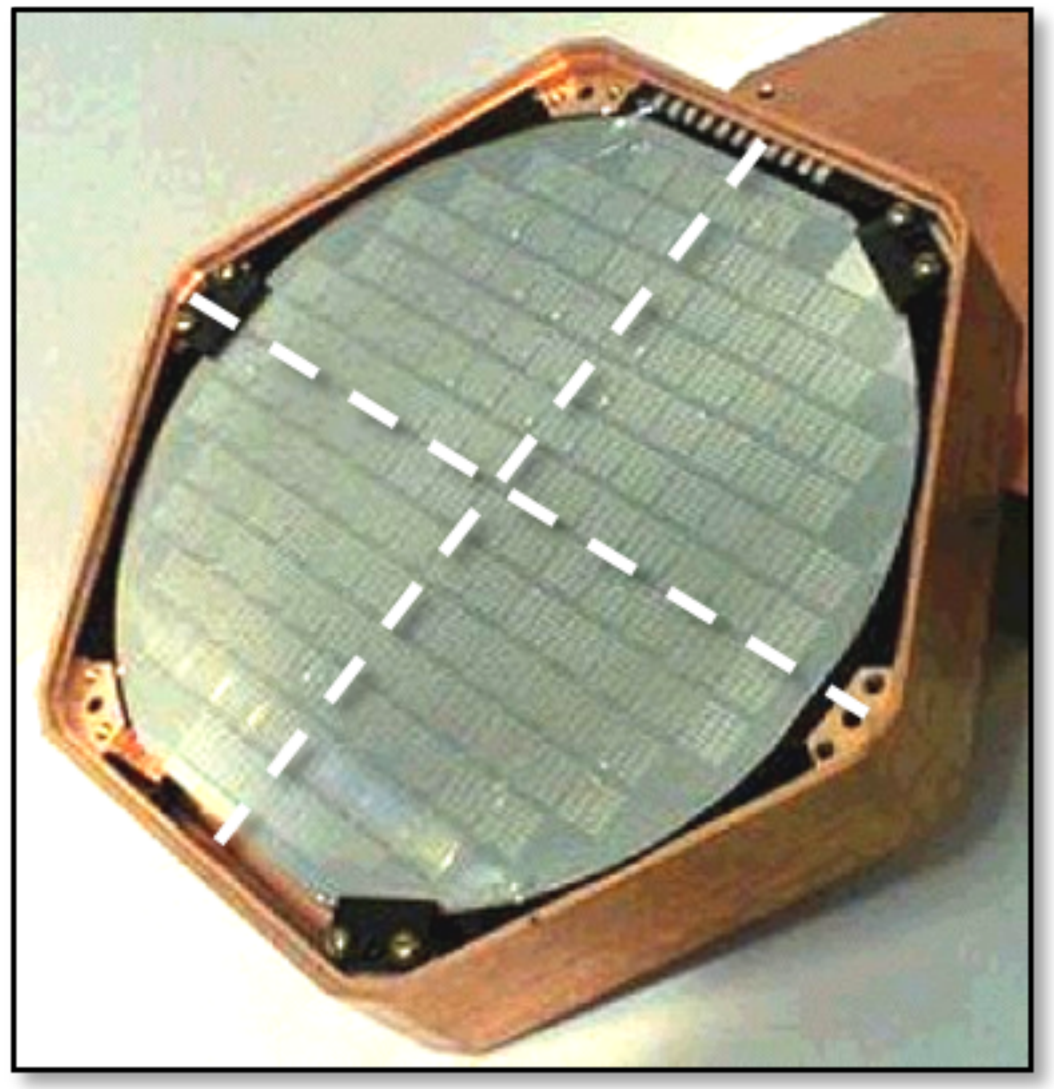
$$C_{scalar} = \frac{1}{\pi G_F^2}\left[Z f_p + (A - Z) f_n\right]^2$$



Other methods have been proposed, which do not treat the nucleus as a point-like particle. These are not discussed here. See, for example, Haxton et al, JCAP 1302 (2013) 004

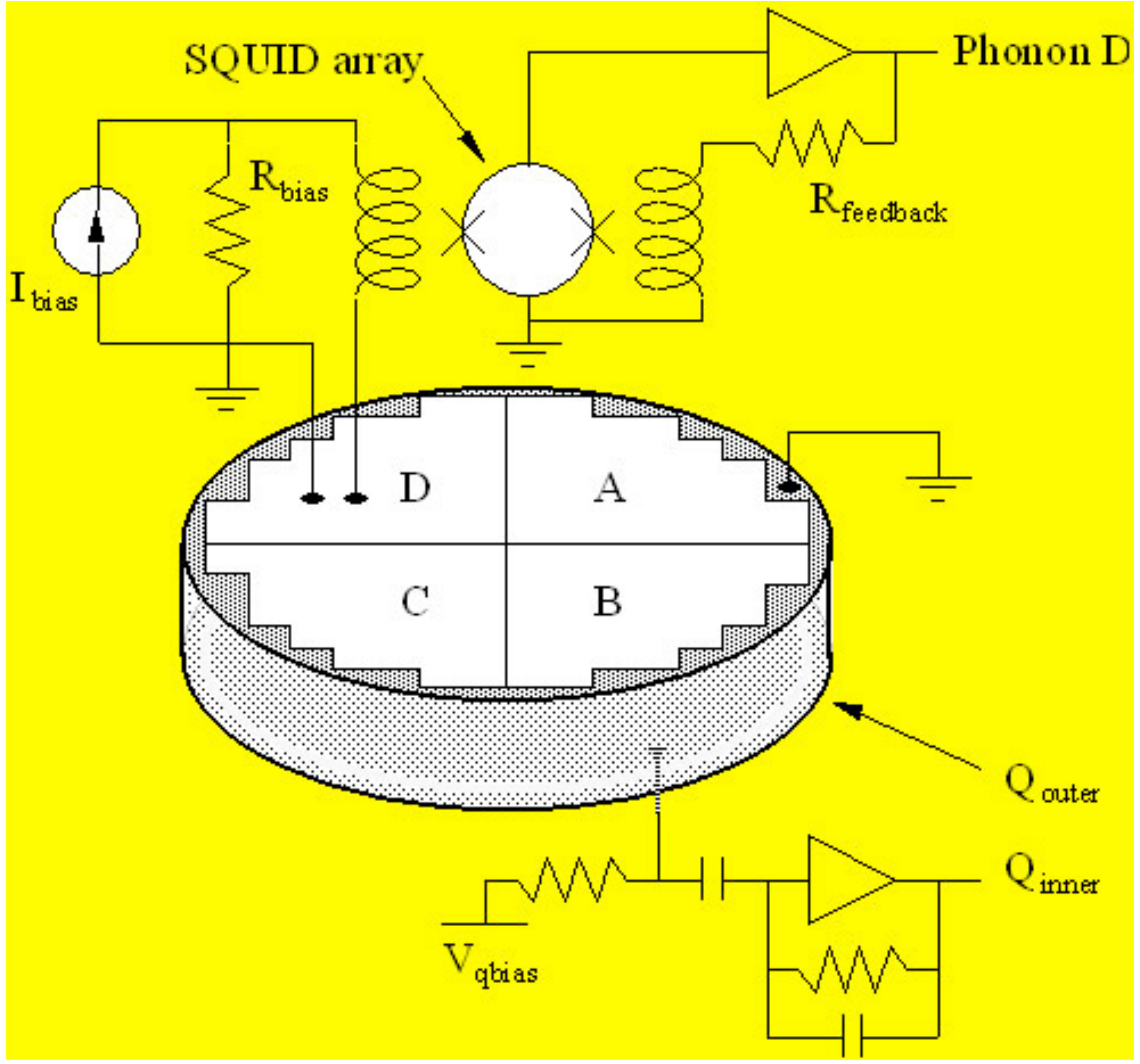
Cryogenic Experiments - CDMS

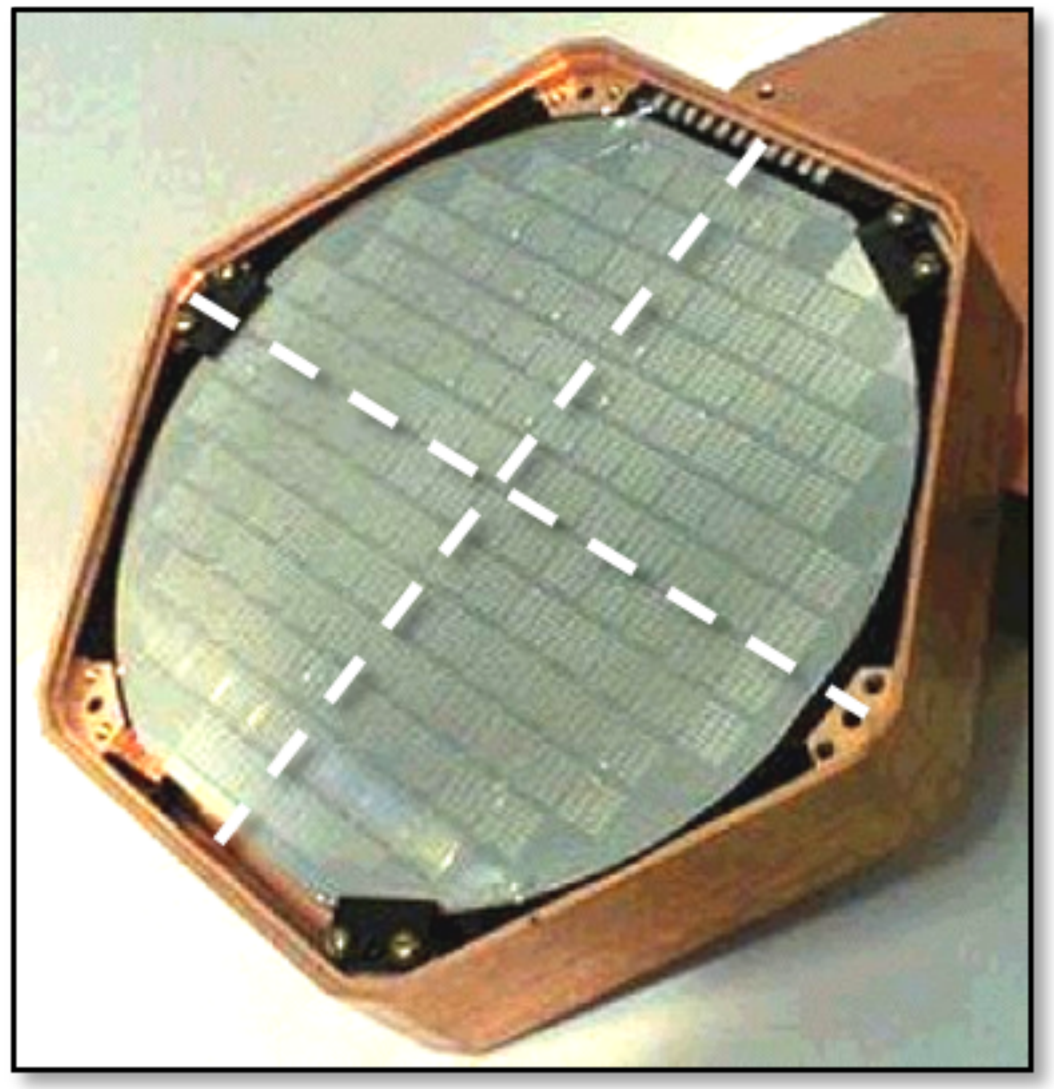


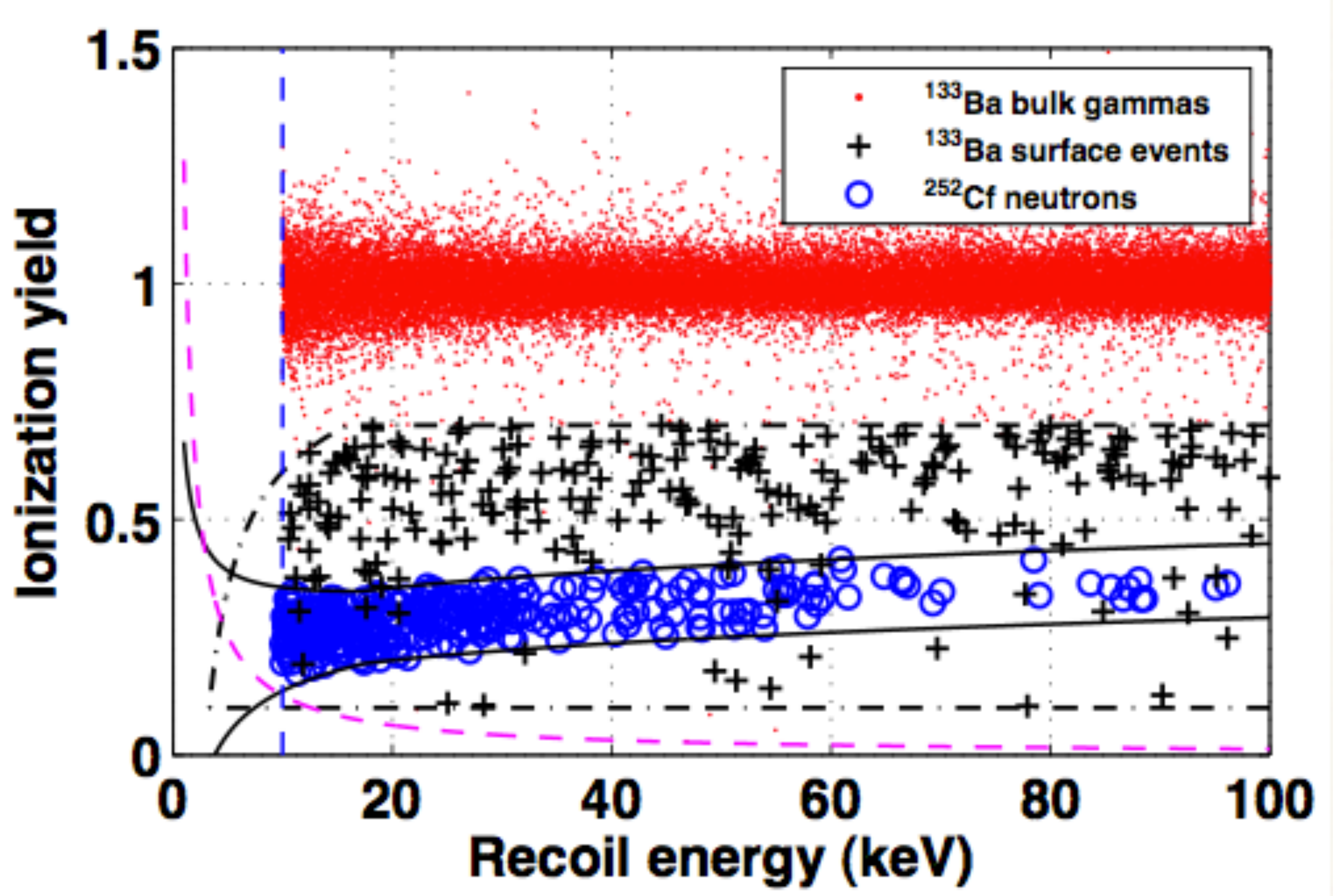


Criterion 1: Sensitive to small deposits of energy

Cryogenic Experiments - CDMS



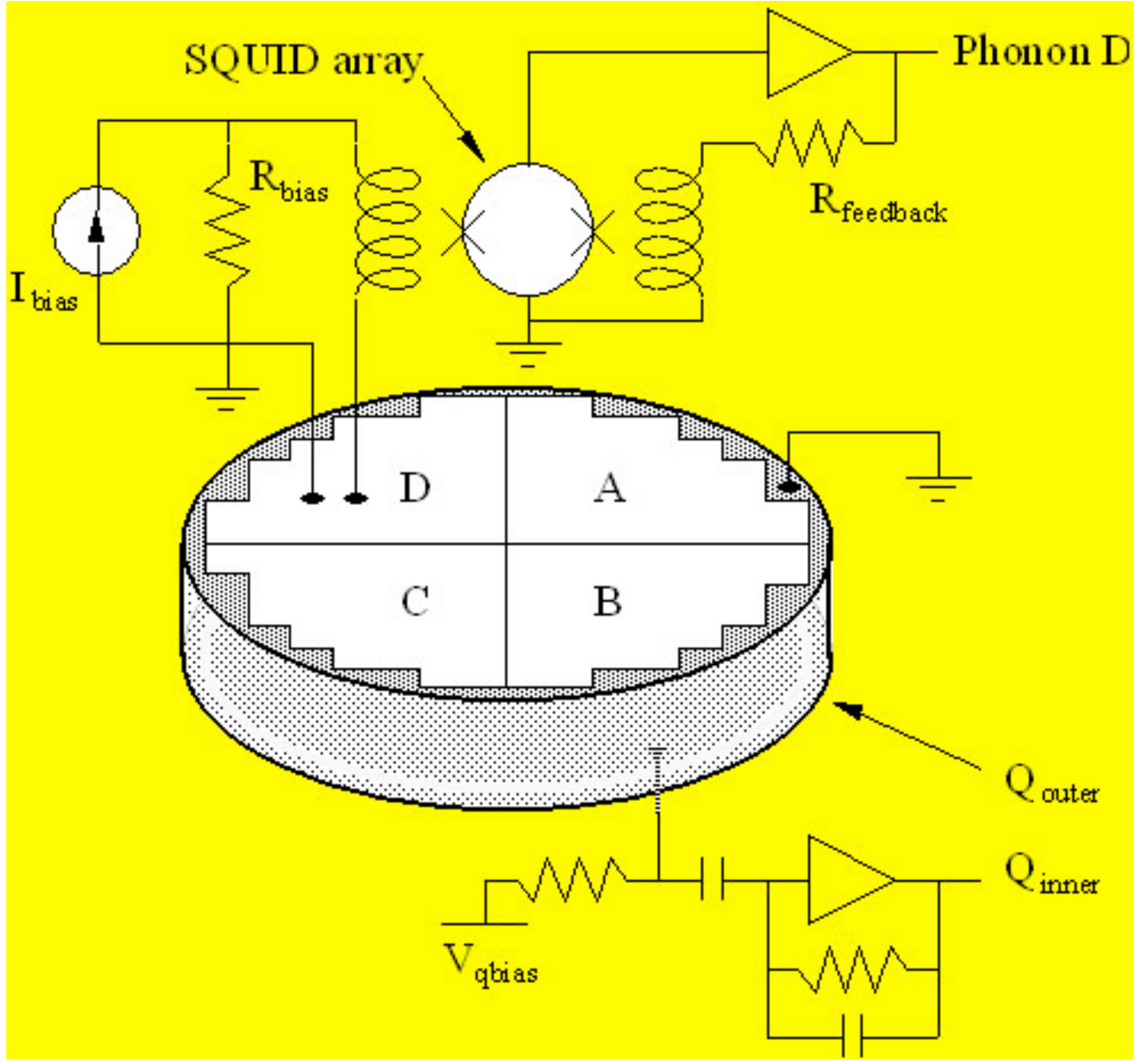


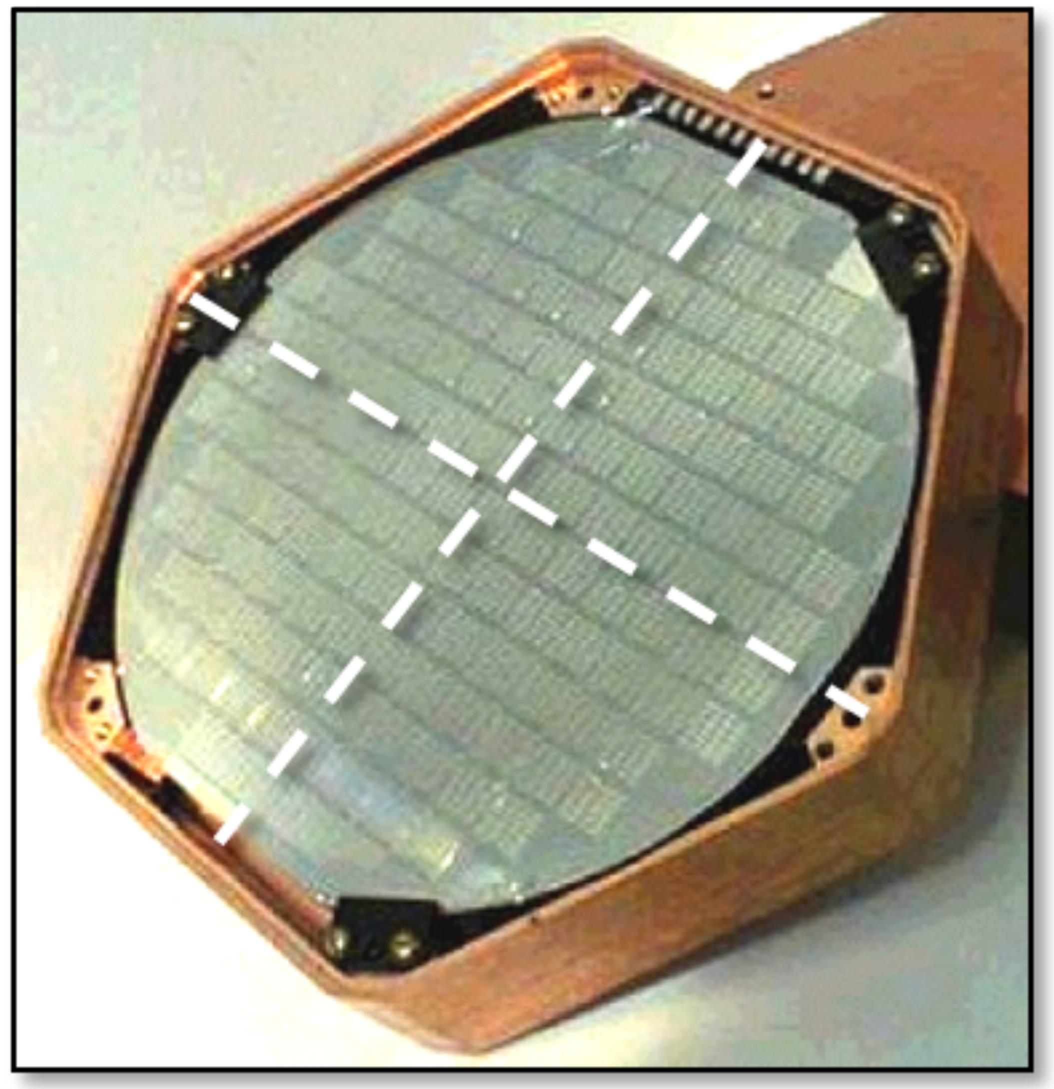


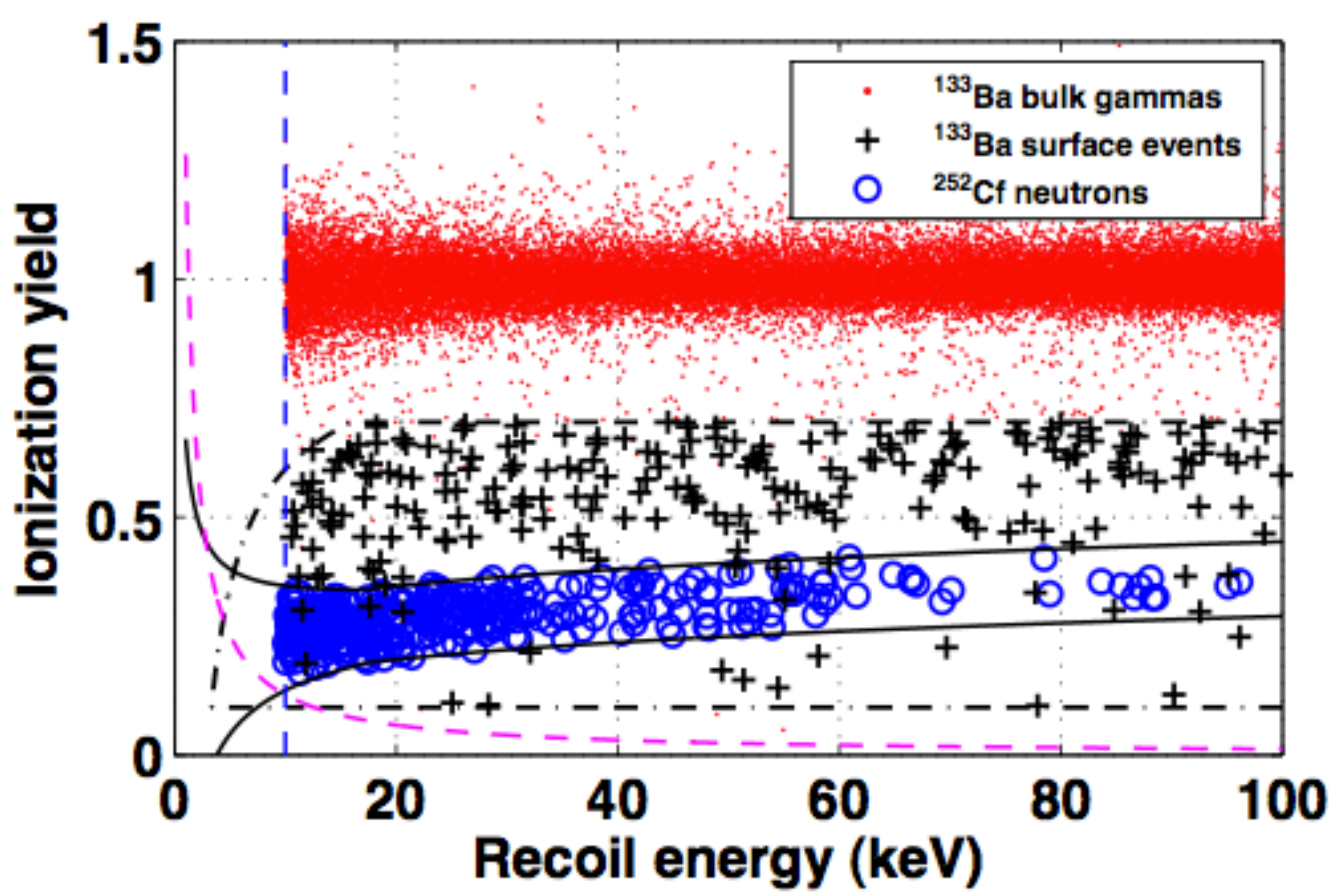
Criterion 1: Sensitive to small deposits of energy

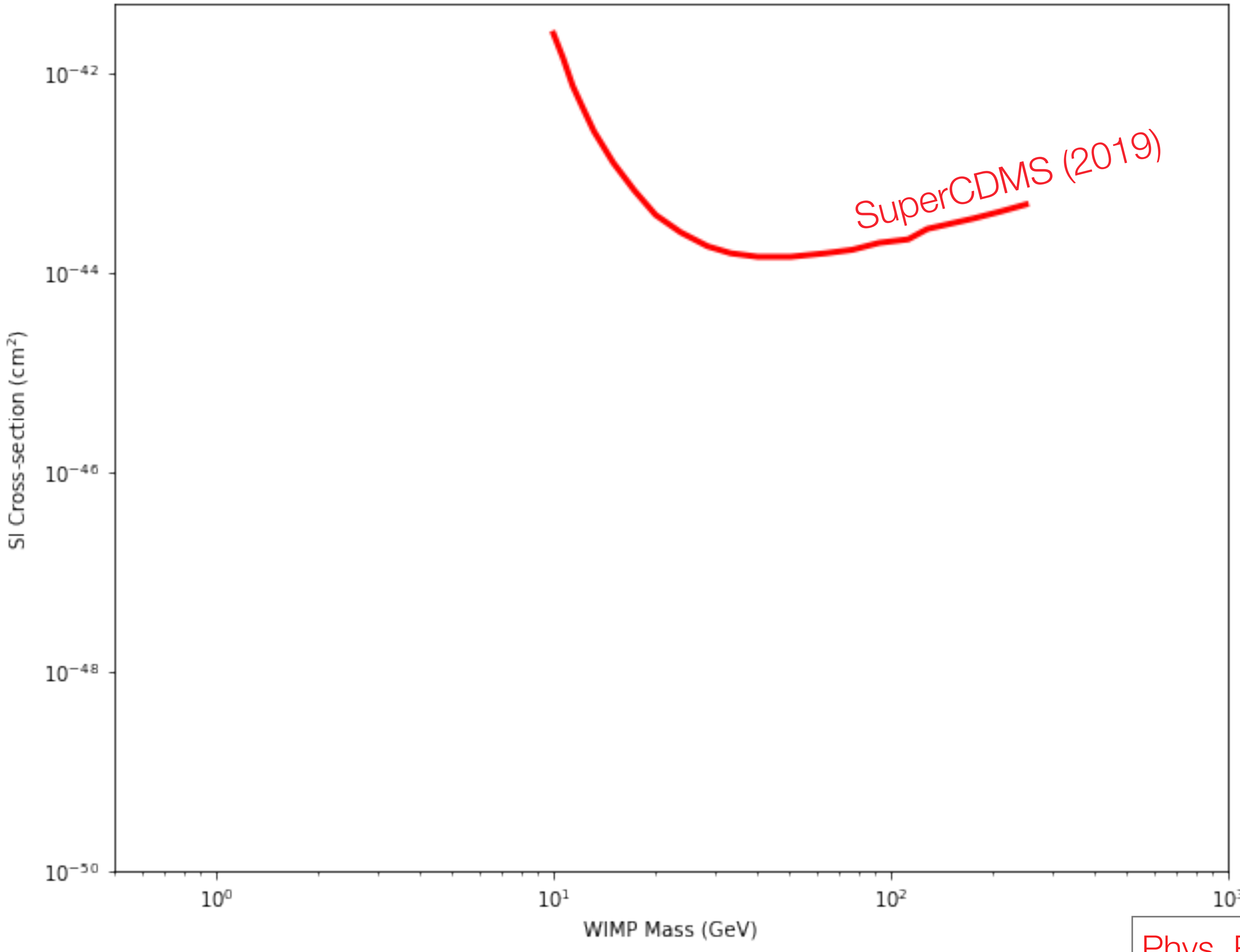
Criterion 2: Method of discrimination of backgrounds

Cryogenic Experiments - CDMS



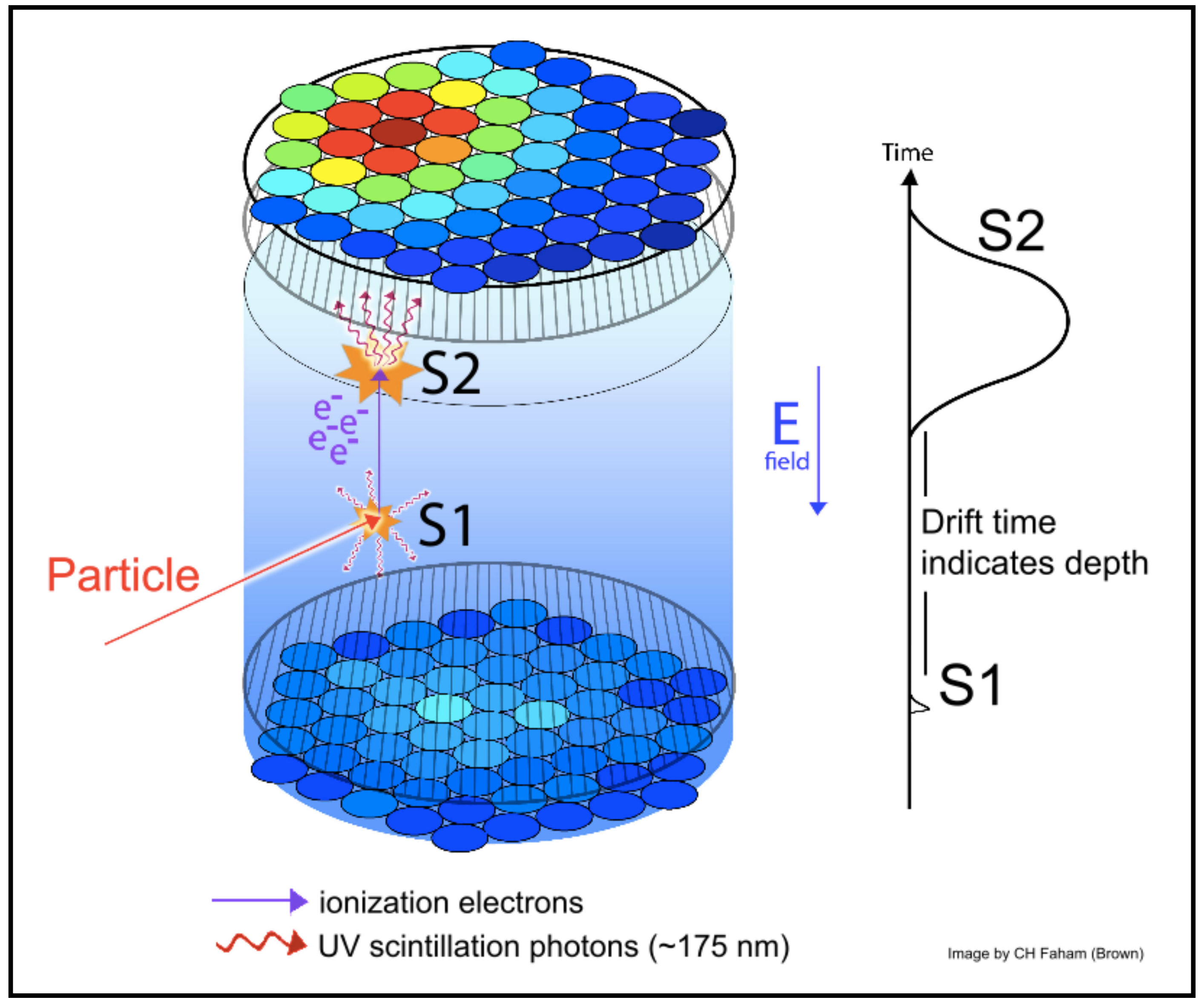






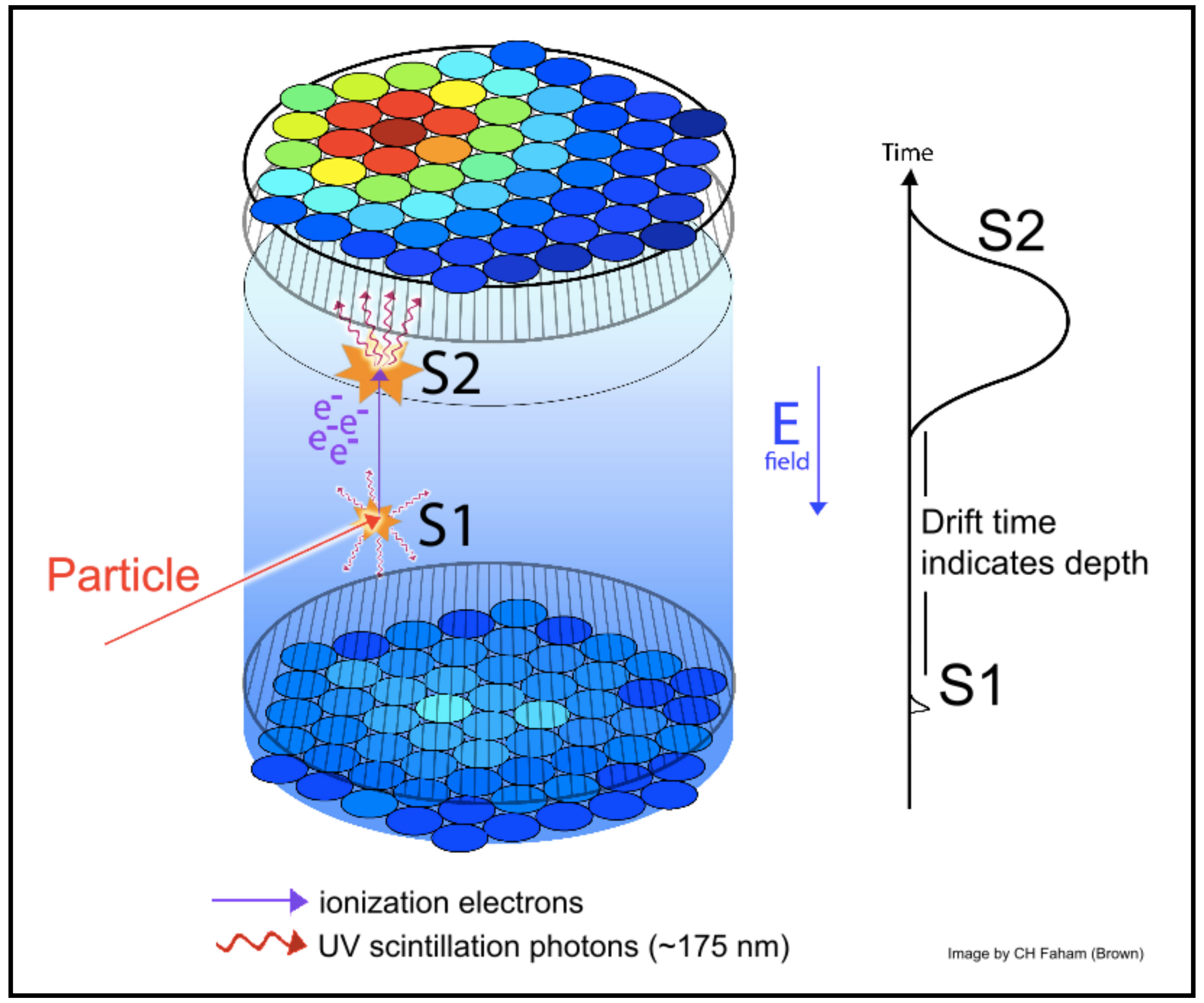
Phys. Rev. Lett. **120** 6 061802

Noble Liquid Experiments - LUX



Criterion 1: Sensitive to small deposits of energy

Noble Liquid Experiments - LUX



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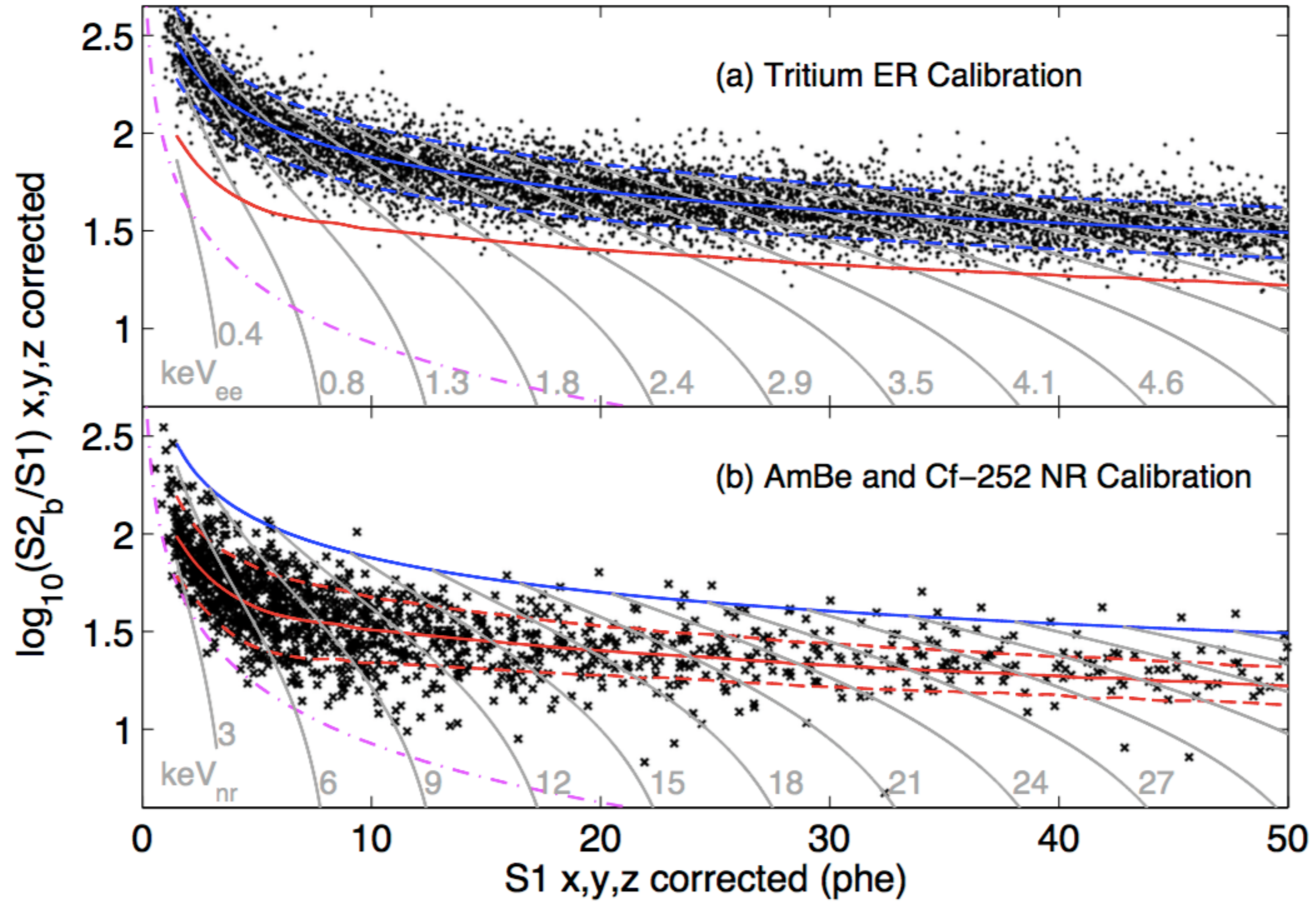
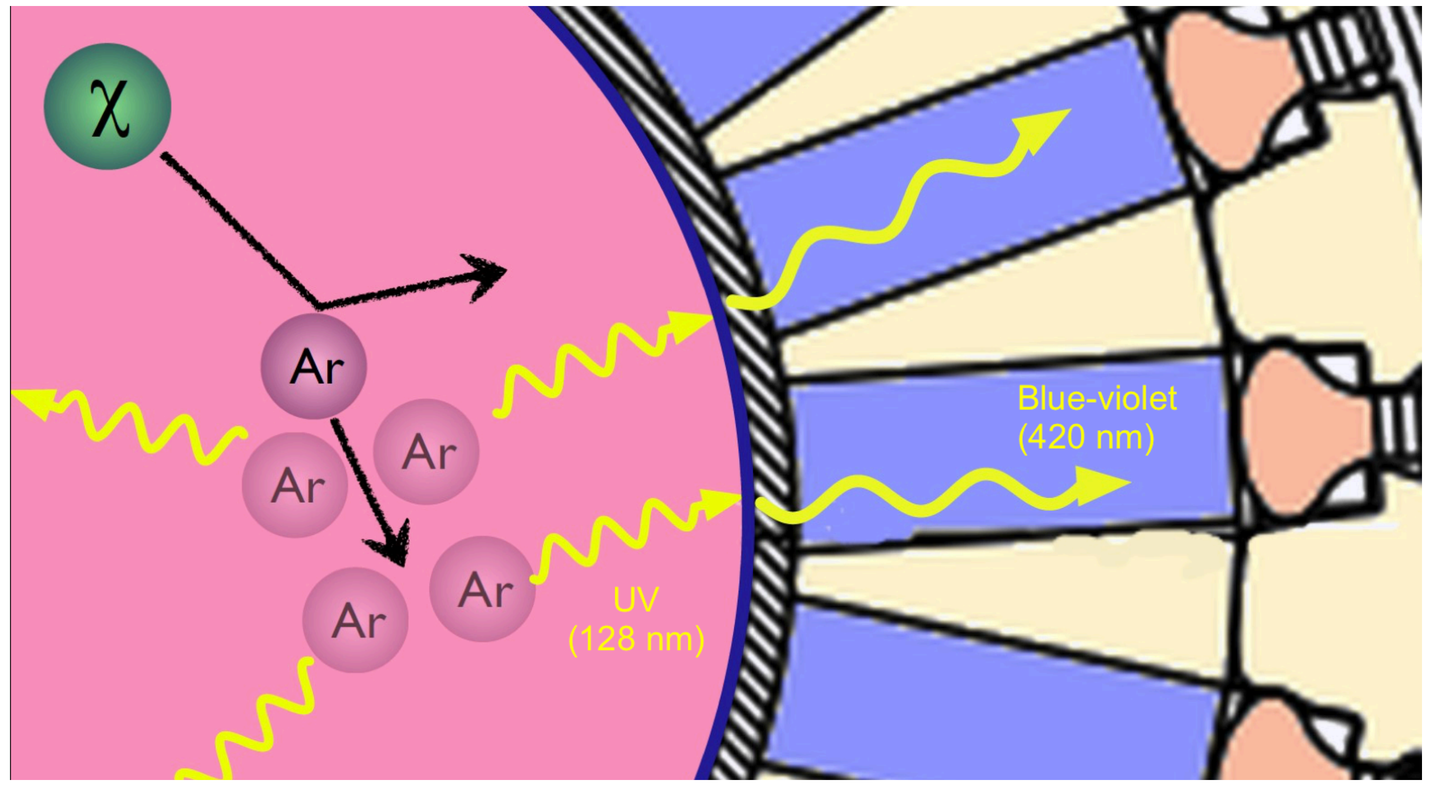
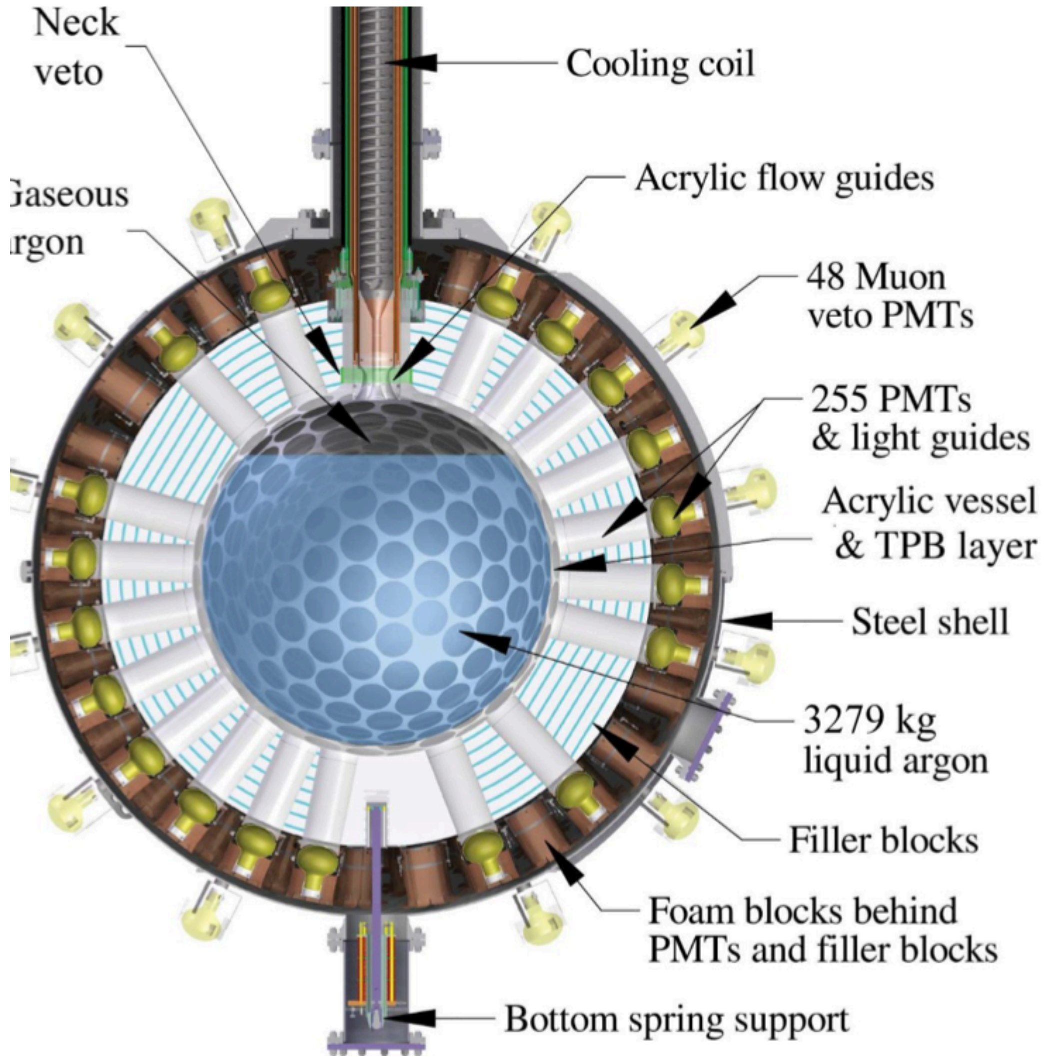


Criterion 2: Method of discrimination of backgrounds

Noble Liquid Experiments - DEAP



Simon Veil, WNPPC 2019



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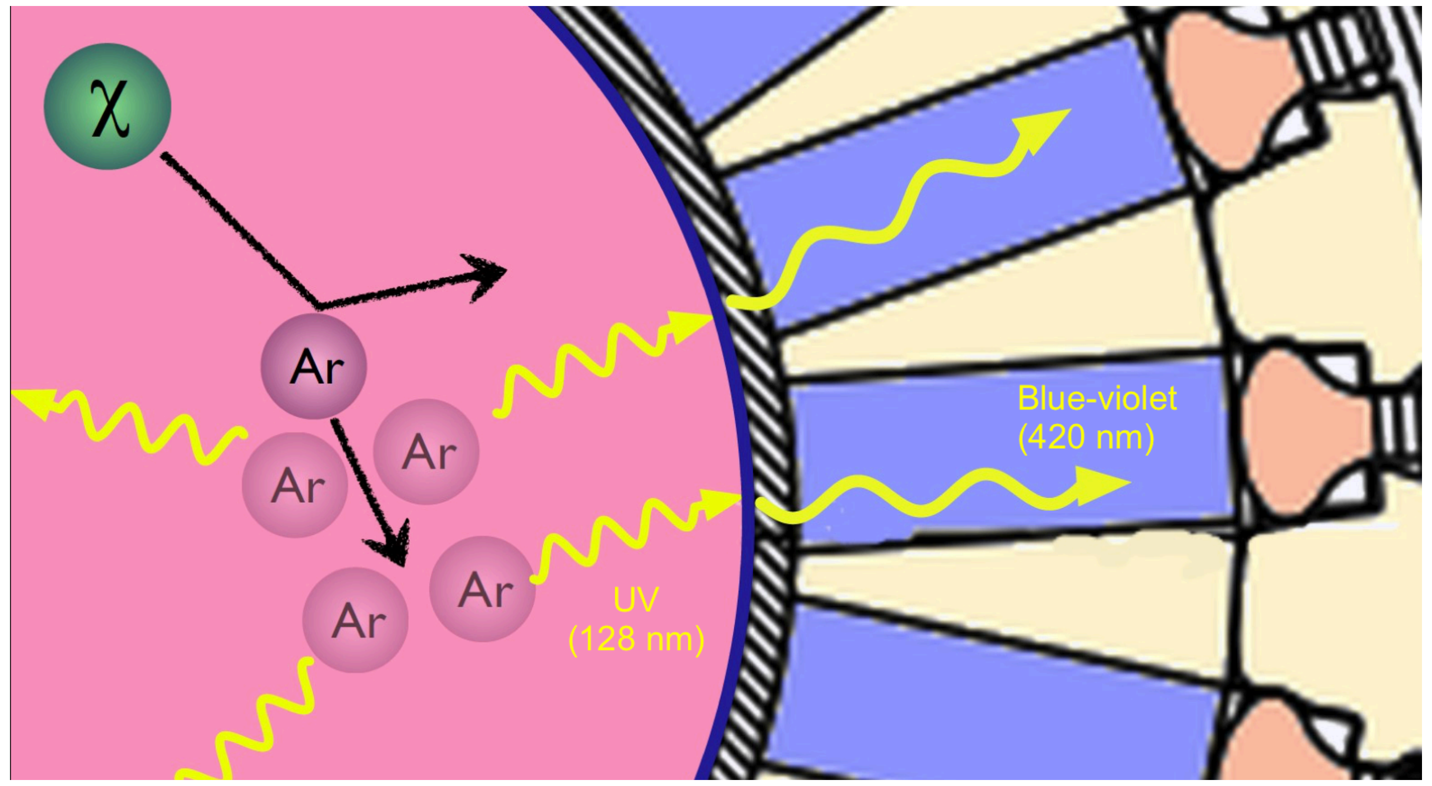

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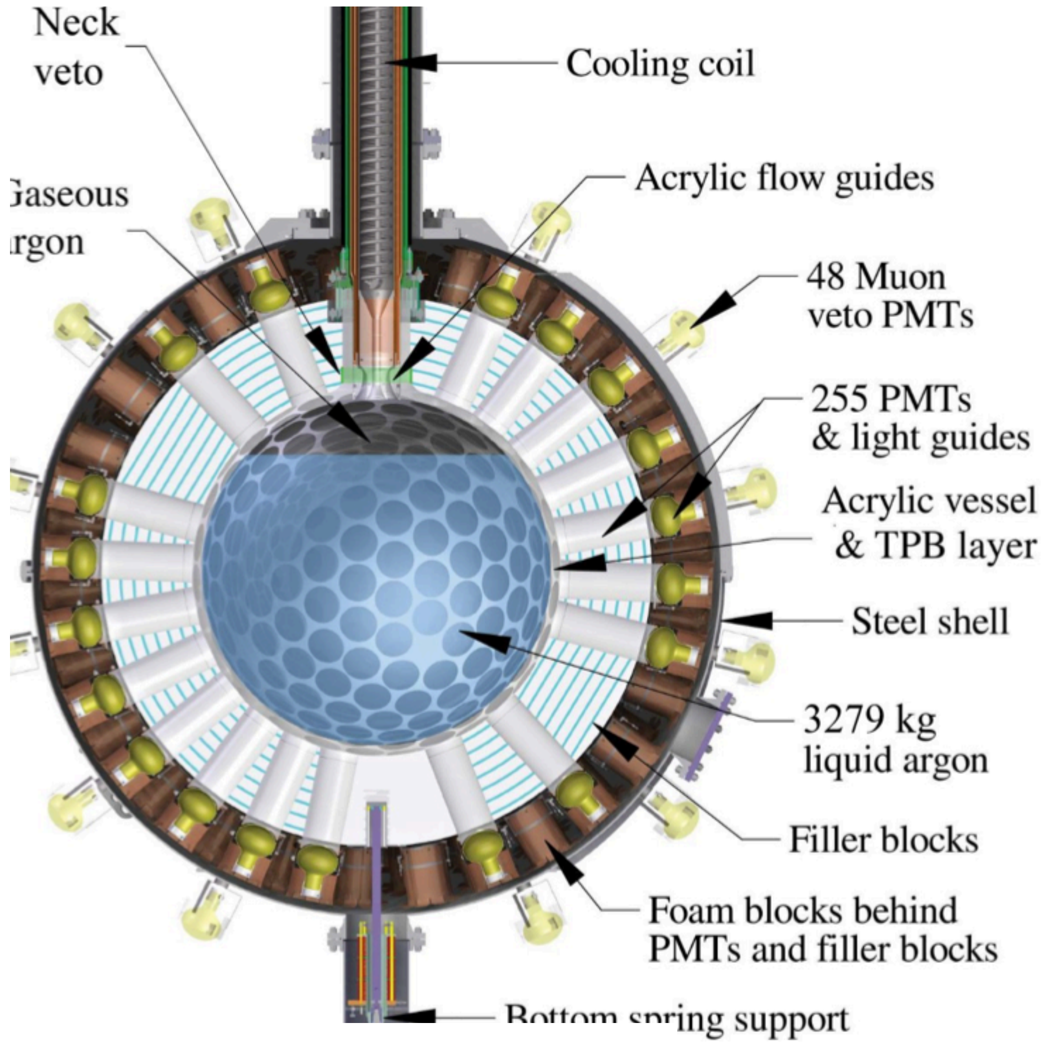
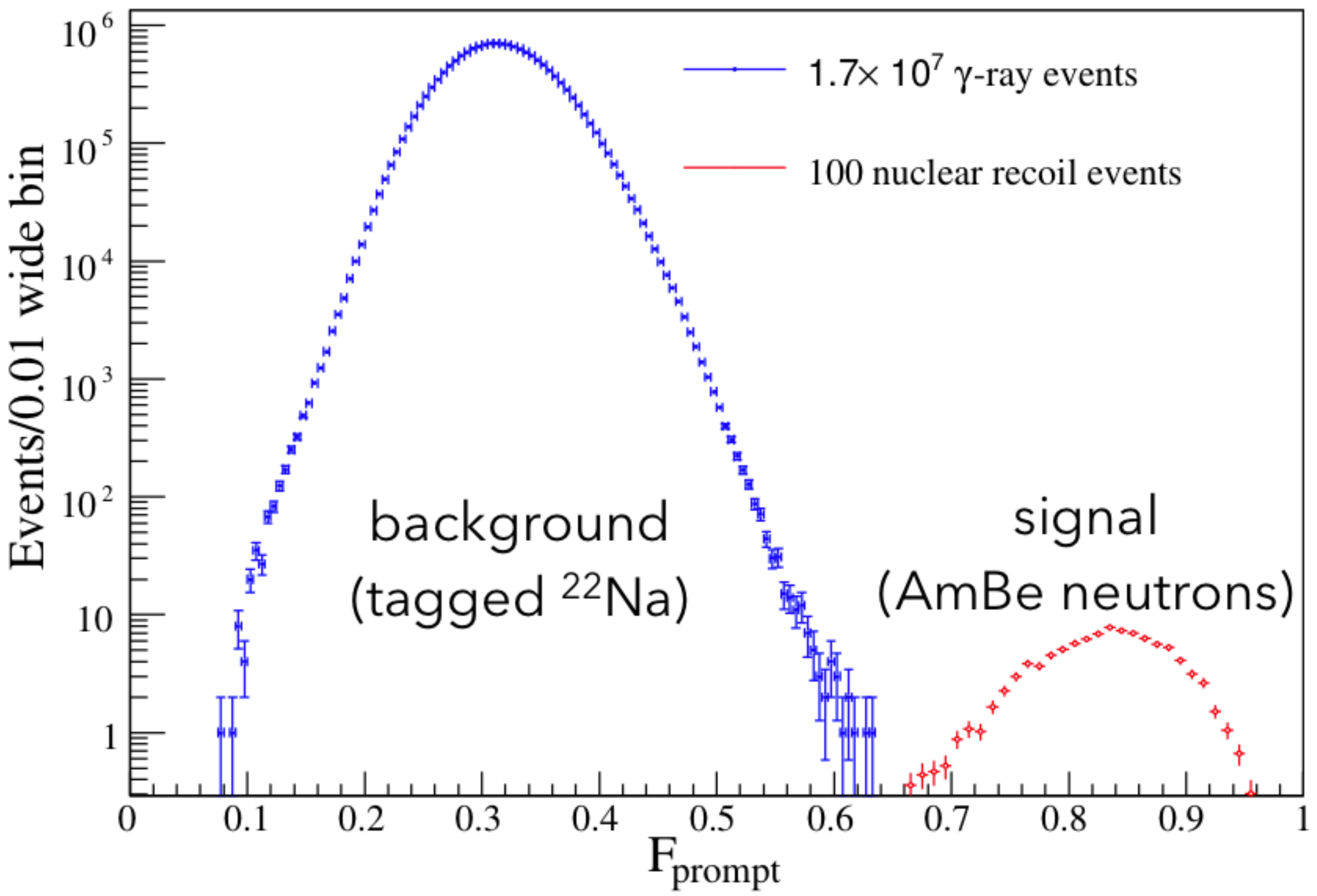


Criterion 1: Sensitive to small deposits of energy

DEAP-1 prototype data



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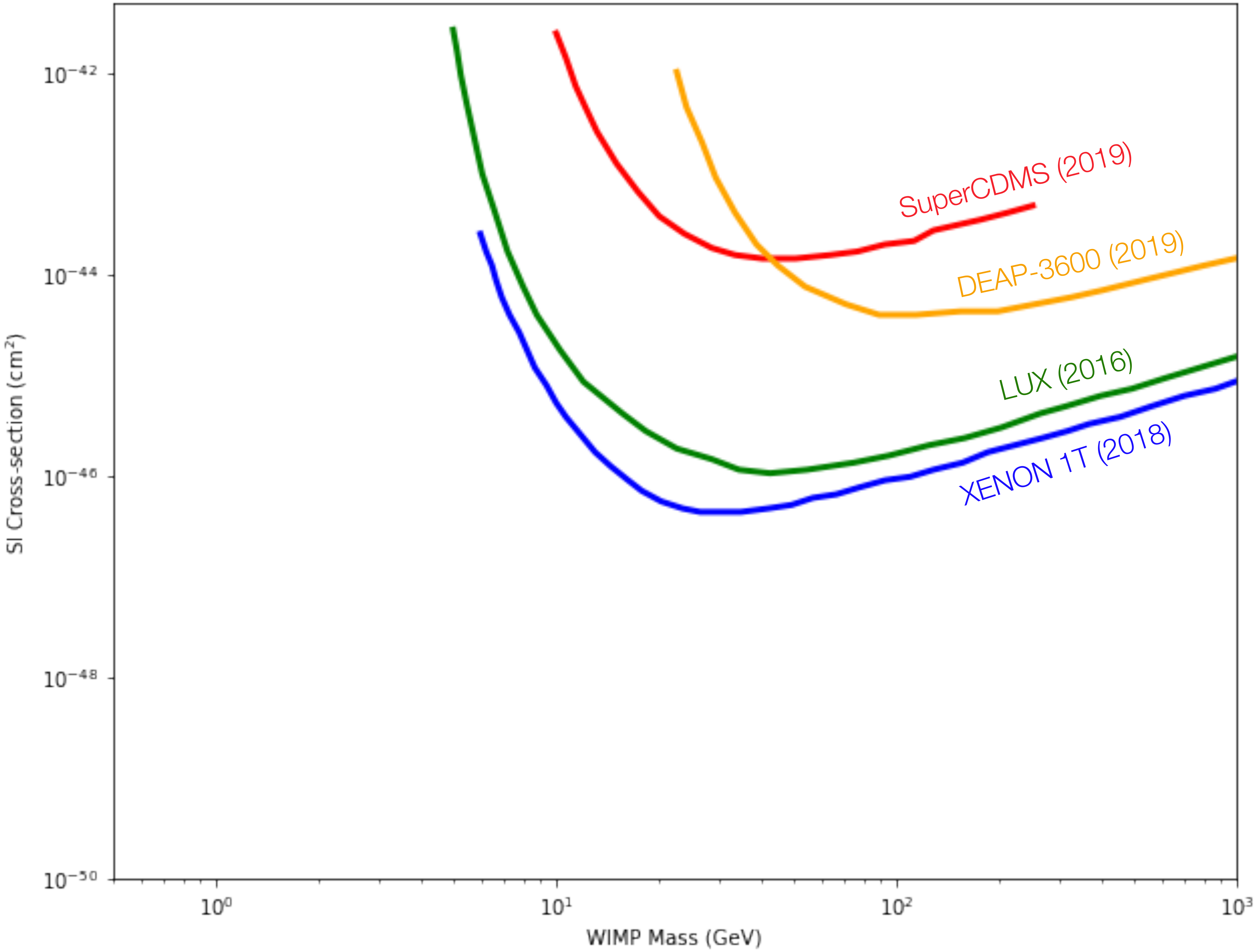
Noble Liquid Experiments



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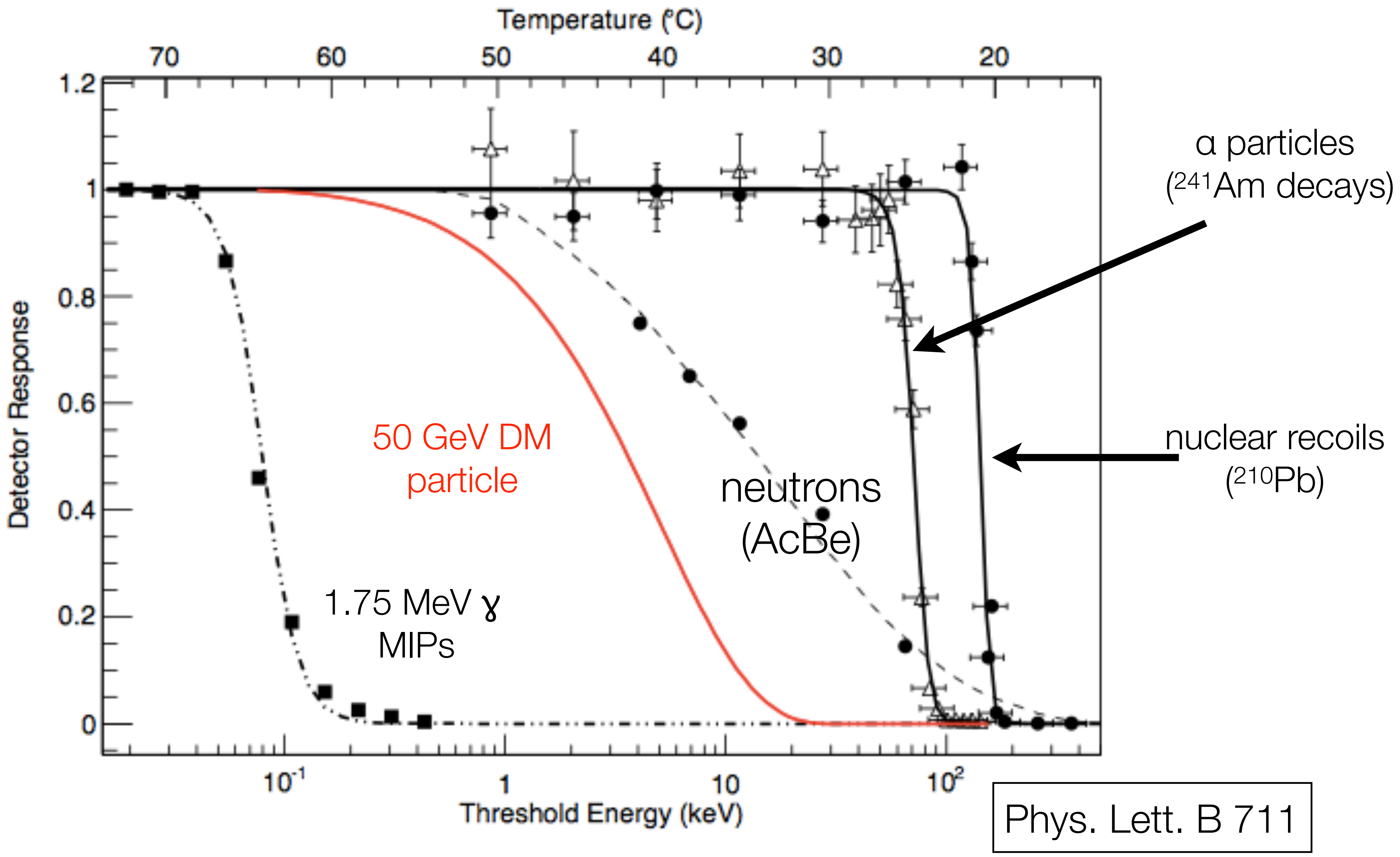
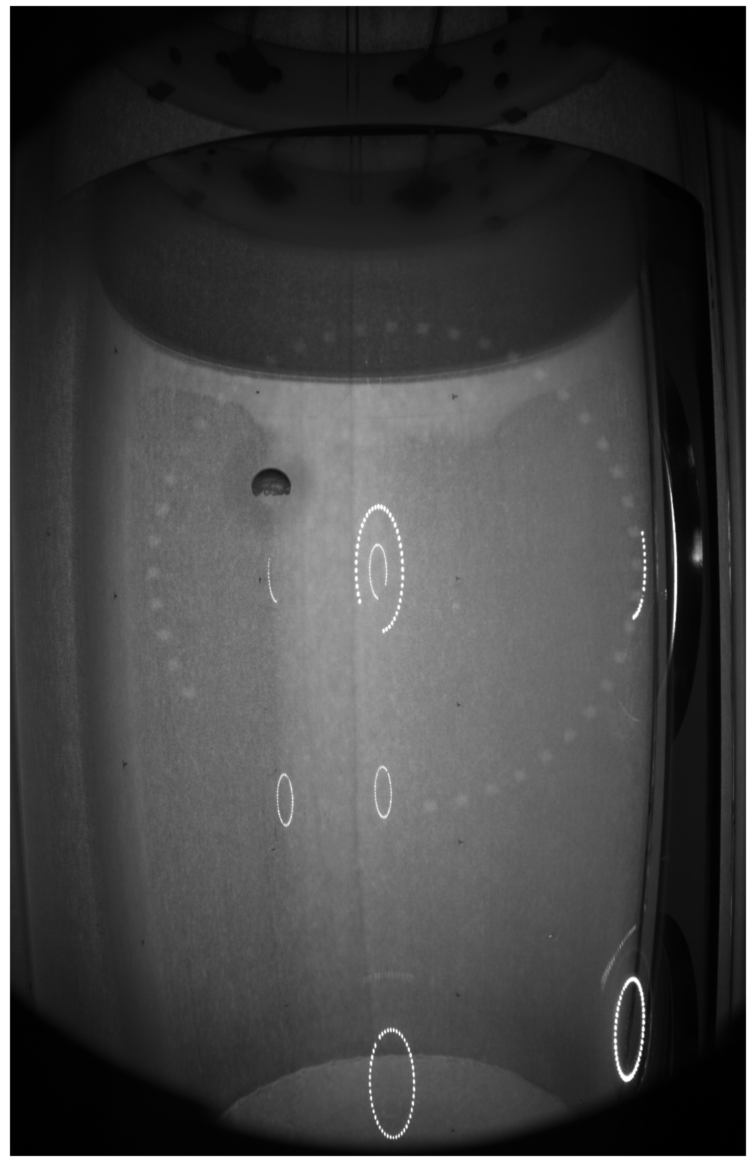
Phys. Rev. Lett. **118**, 16, 161801
Phys. Rev. Lett. **121**, 11, 111302

Superheated Fluid Experiments - PICO



Phys. Lett. B 711



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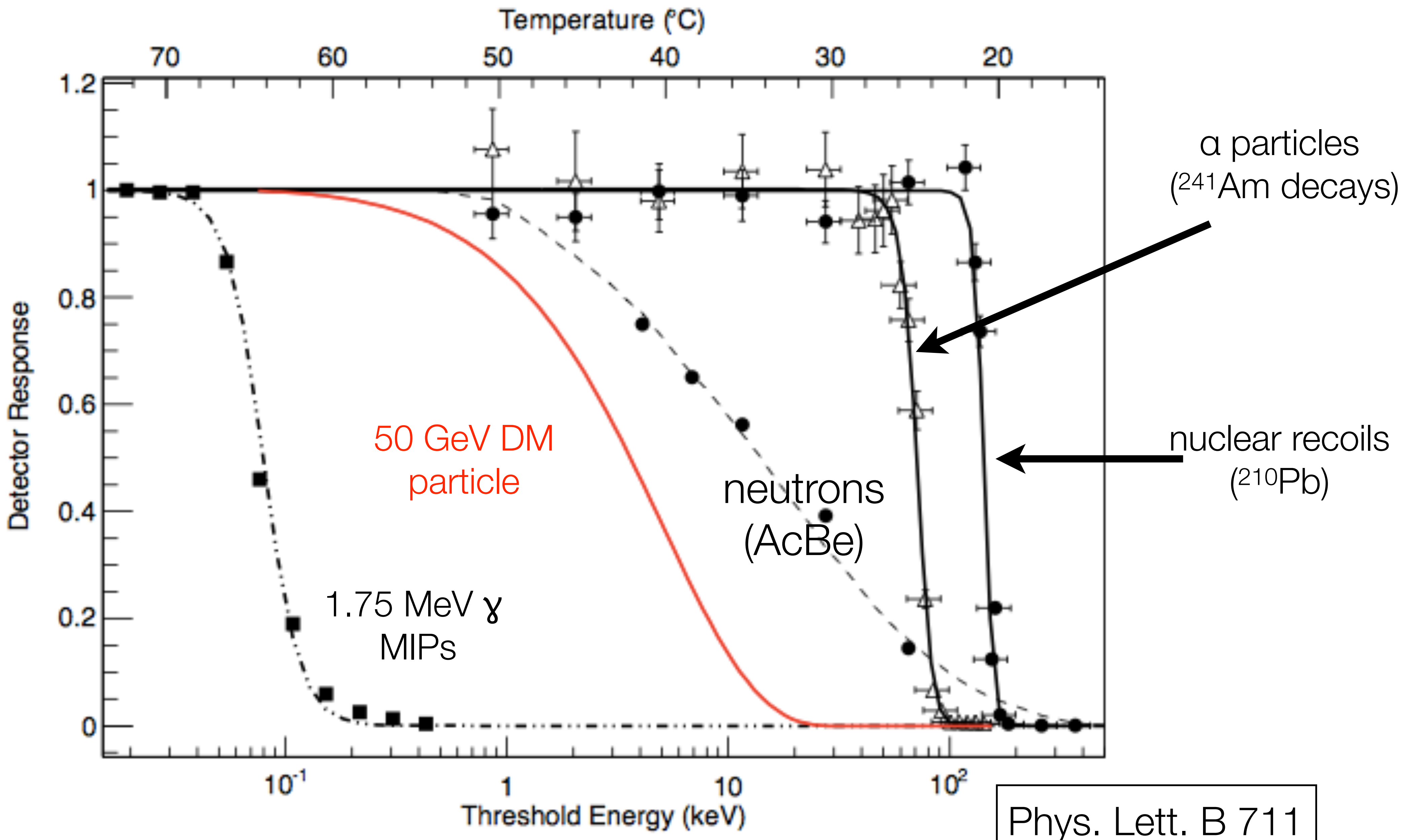
Superheated Fluid Experiments - PICO



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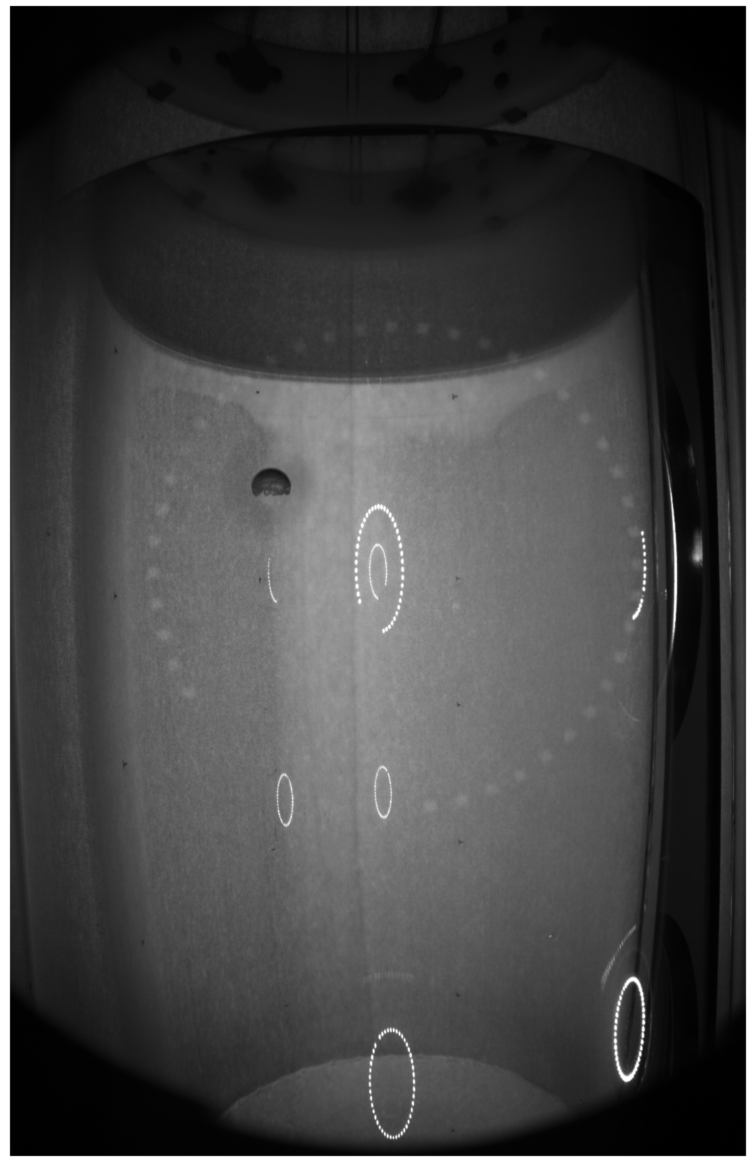

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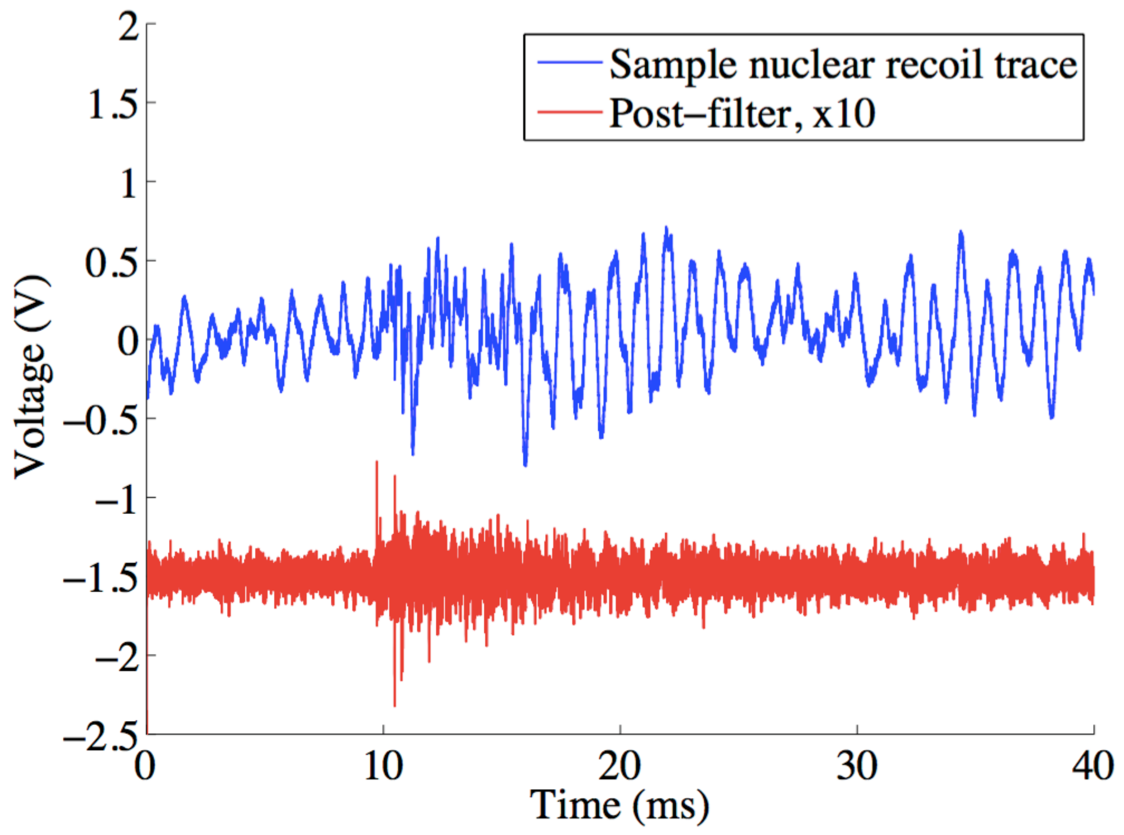
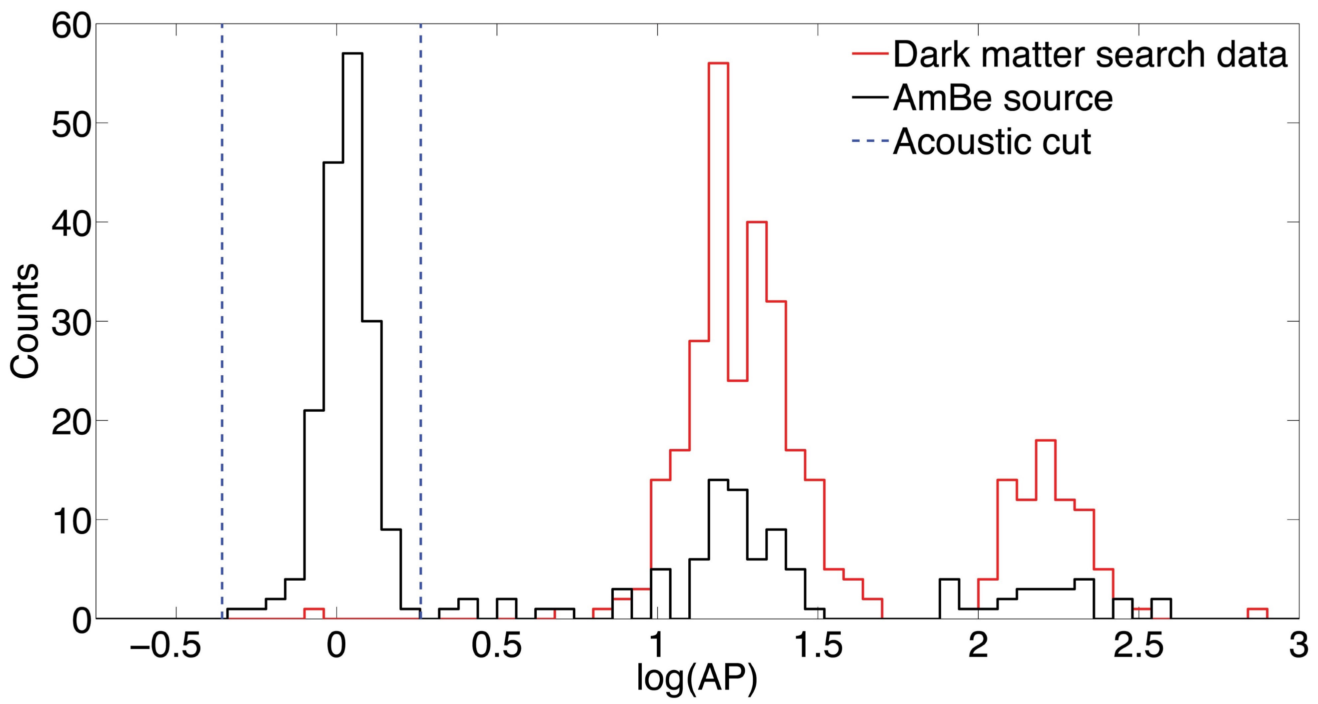
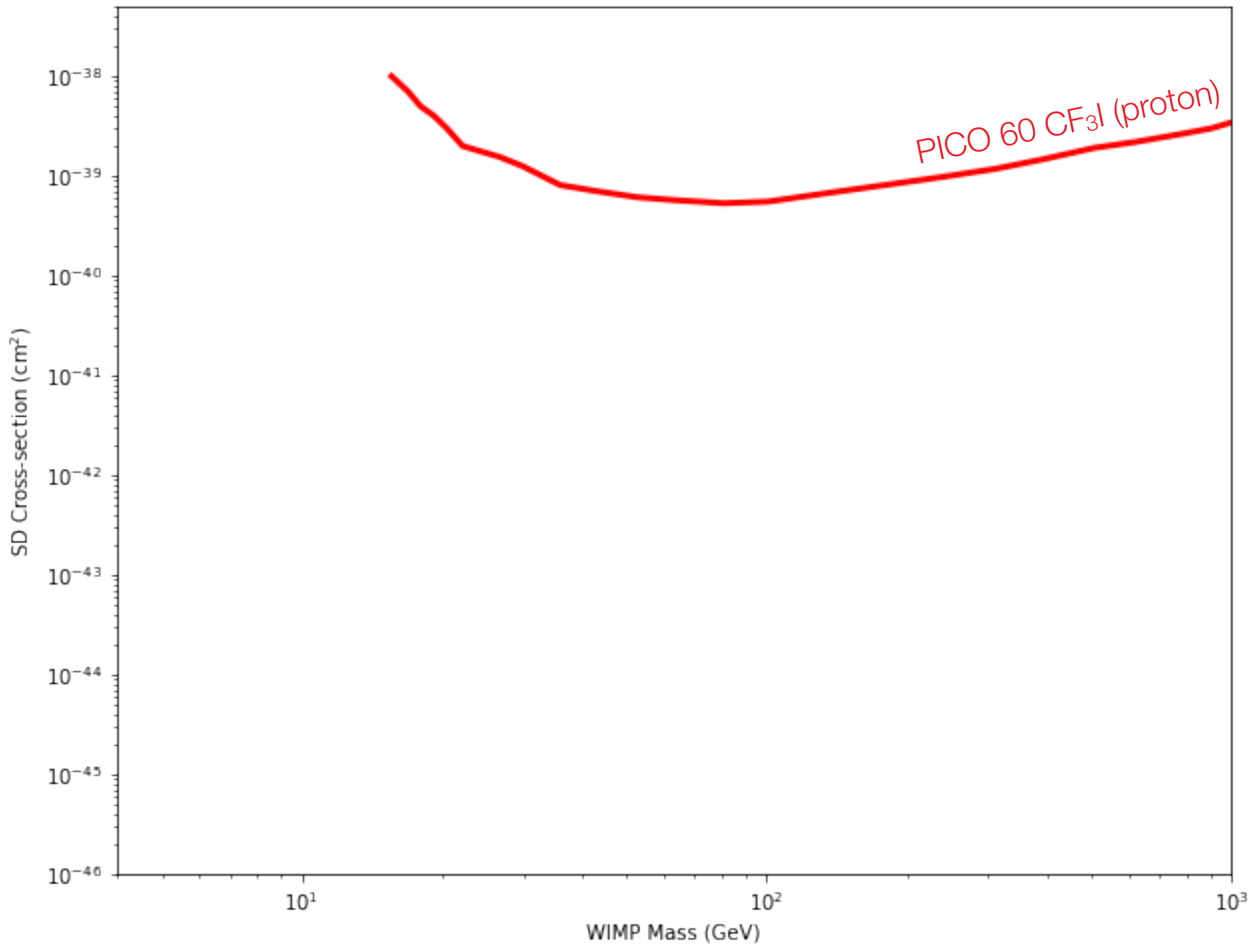




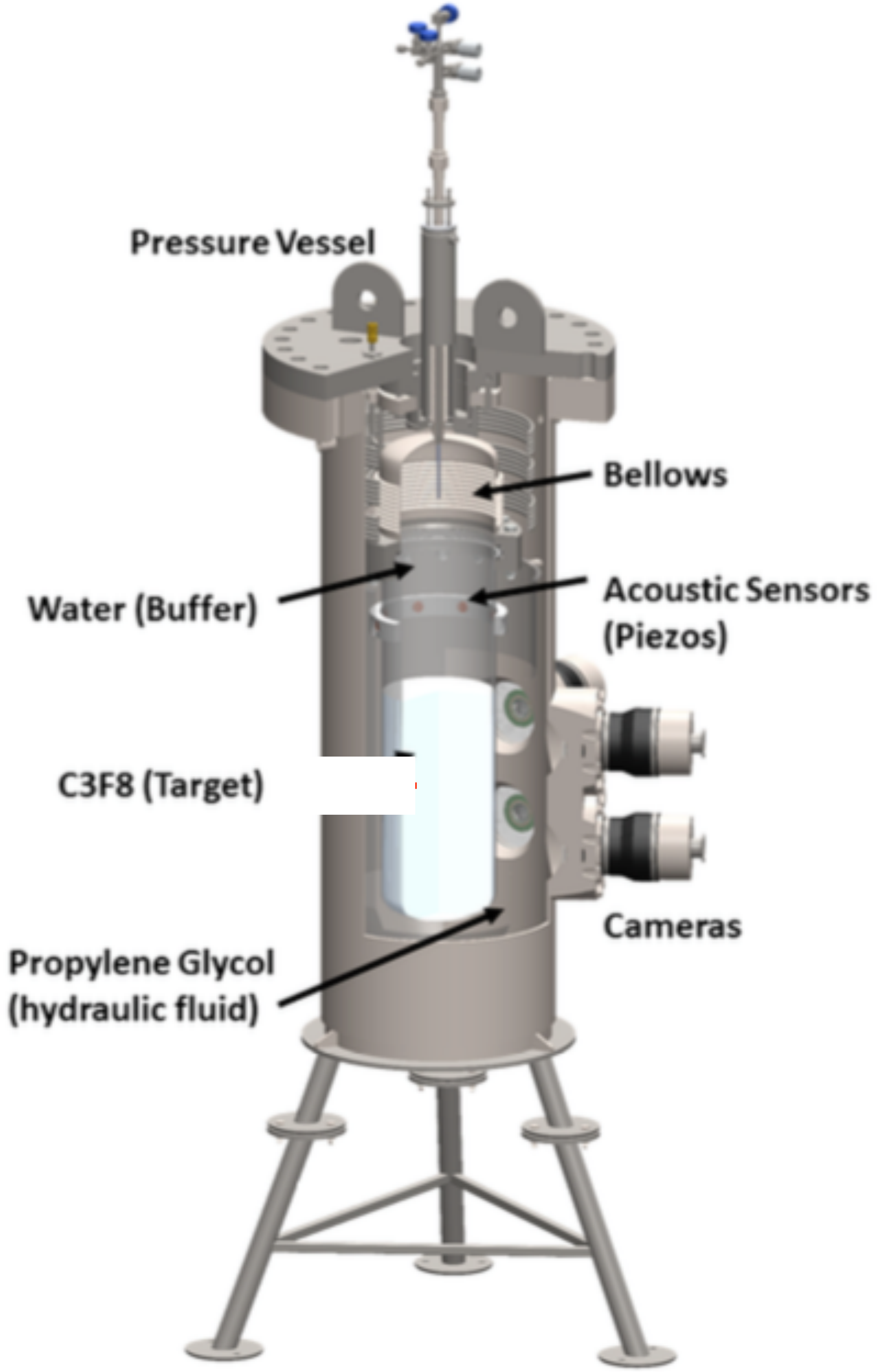
Criterion 2: Method of discrimination of backgrounds

PICO Results



Phys. Rev. D **93**, 052014

Flexible Target

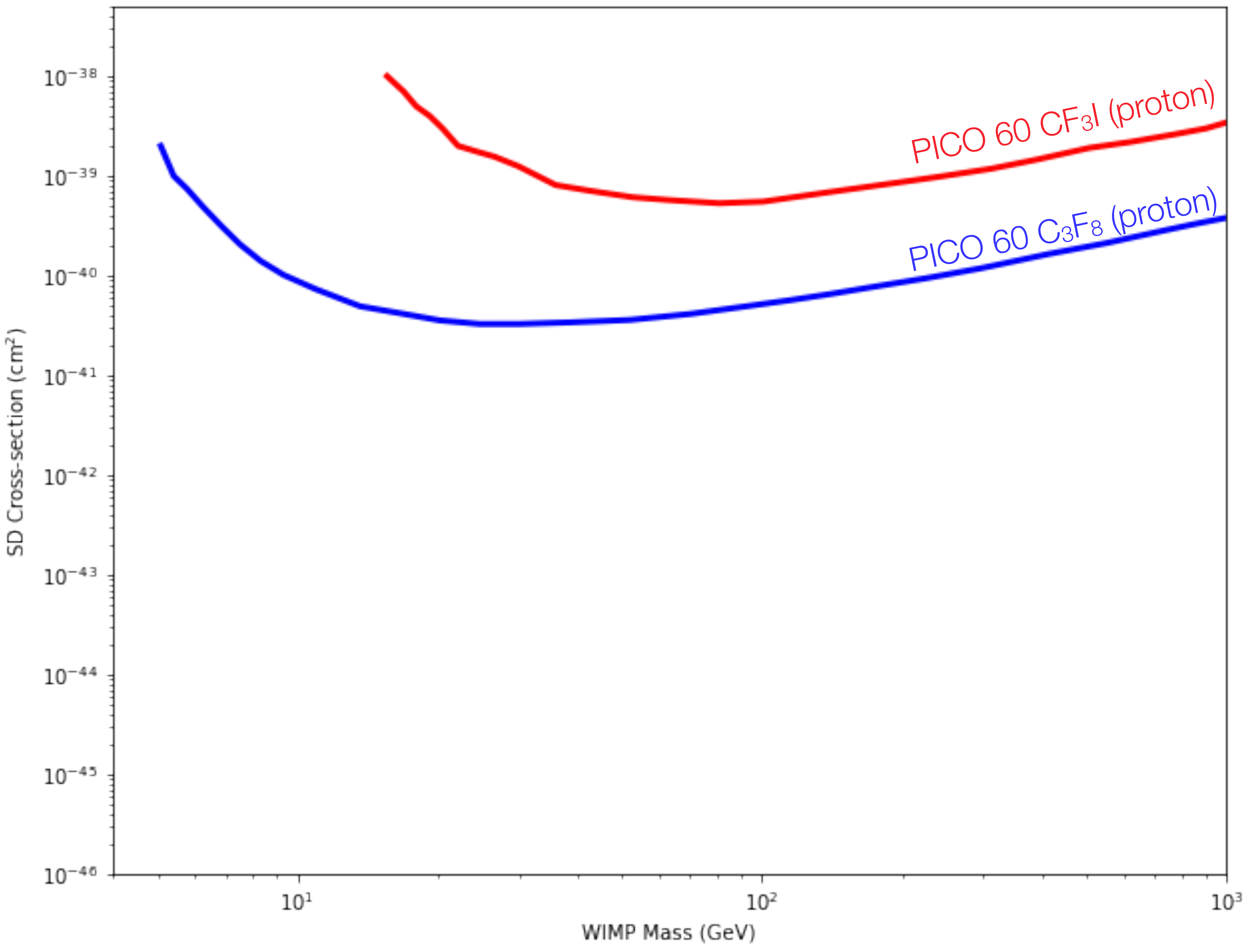


Ability to change target material is very valuable in the hunt for an unknown particle

Nucleus	Z	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{17}O	8	5/2	0	0.495
^{19}F	9	1/2	0.441	-0.109
^{23}Na	11	3/2	0.248	0.020
^{29}Si	14	1/2	-0.002	0.130
^{73}Ge	32	9/2	0.030	0.378
^{93}Nb	41	9/2	0.460	0.080
^{127}I	53	5/2	0.309	0.075
^{129}Xe	54	1/2	0.028	0.359

KC Thesis (!)

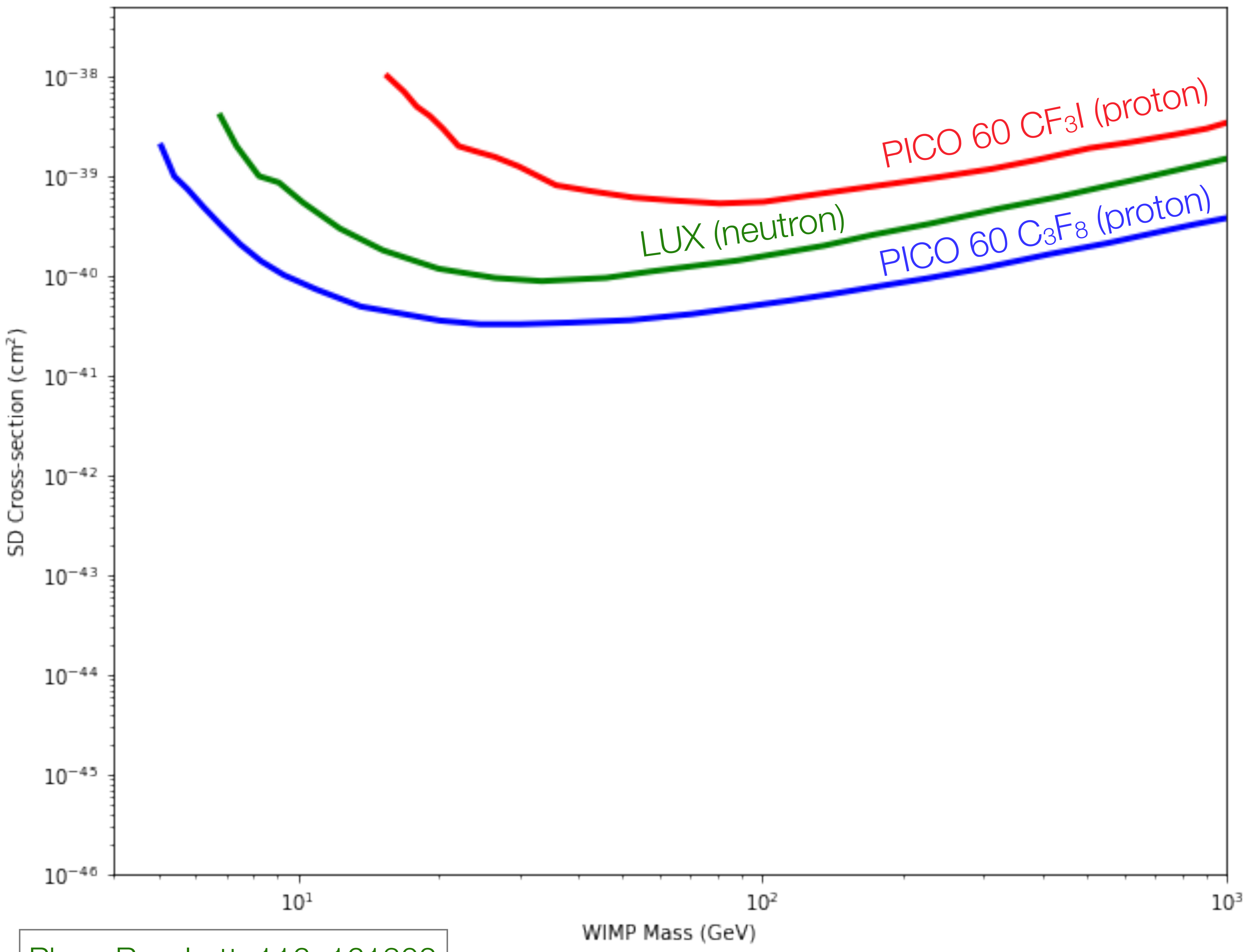
PICO Results



Phys. Rev. Lett. **118**, 251301

State of Experiments

SD Exclusion Limit



Phys. Rev. Lett. 116, 161302

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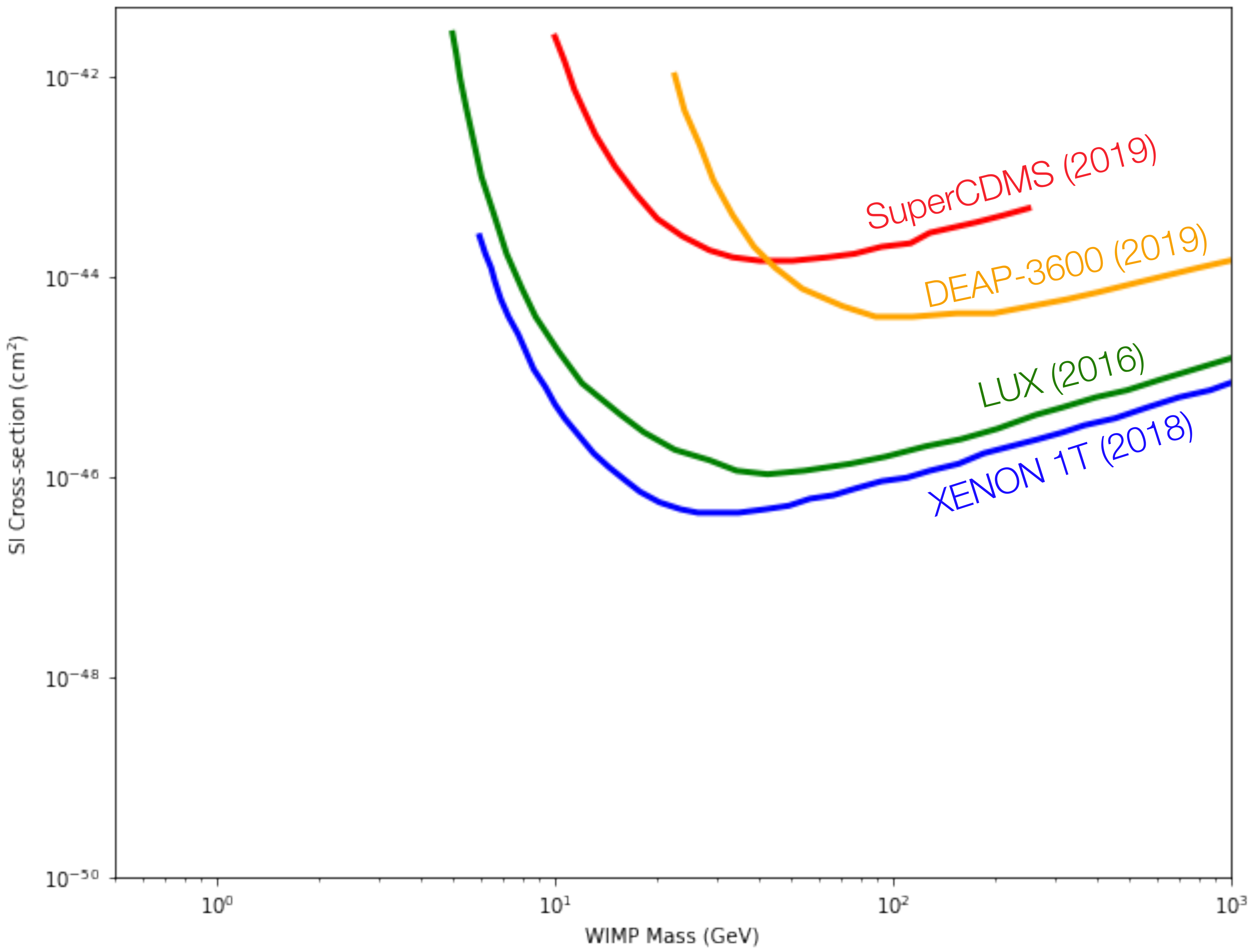

Where do we go now?

State of Experiments

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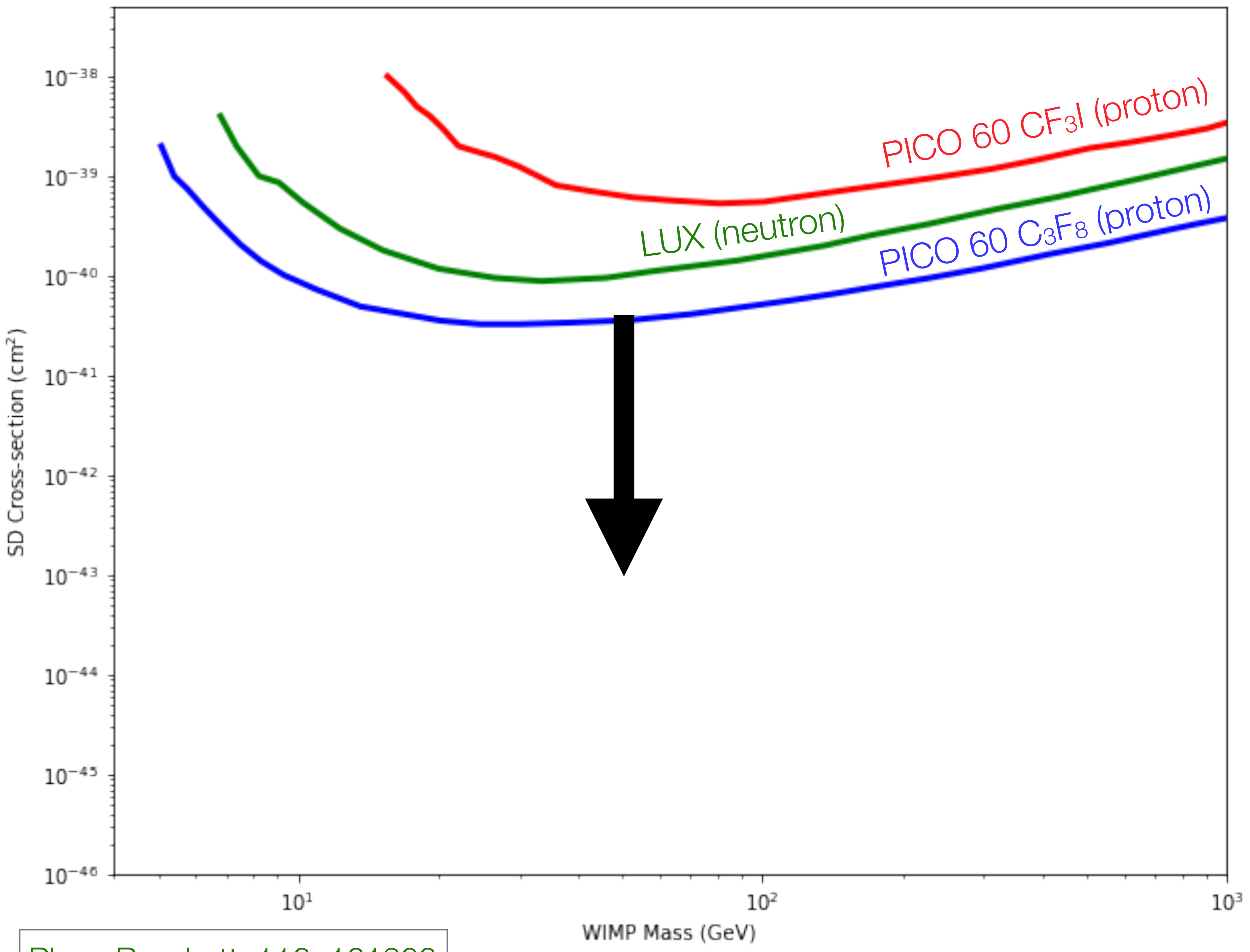

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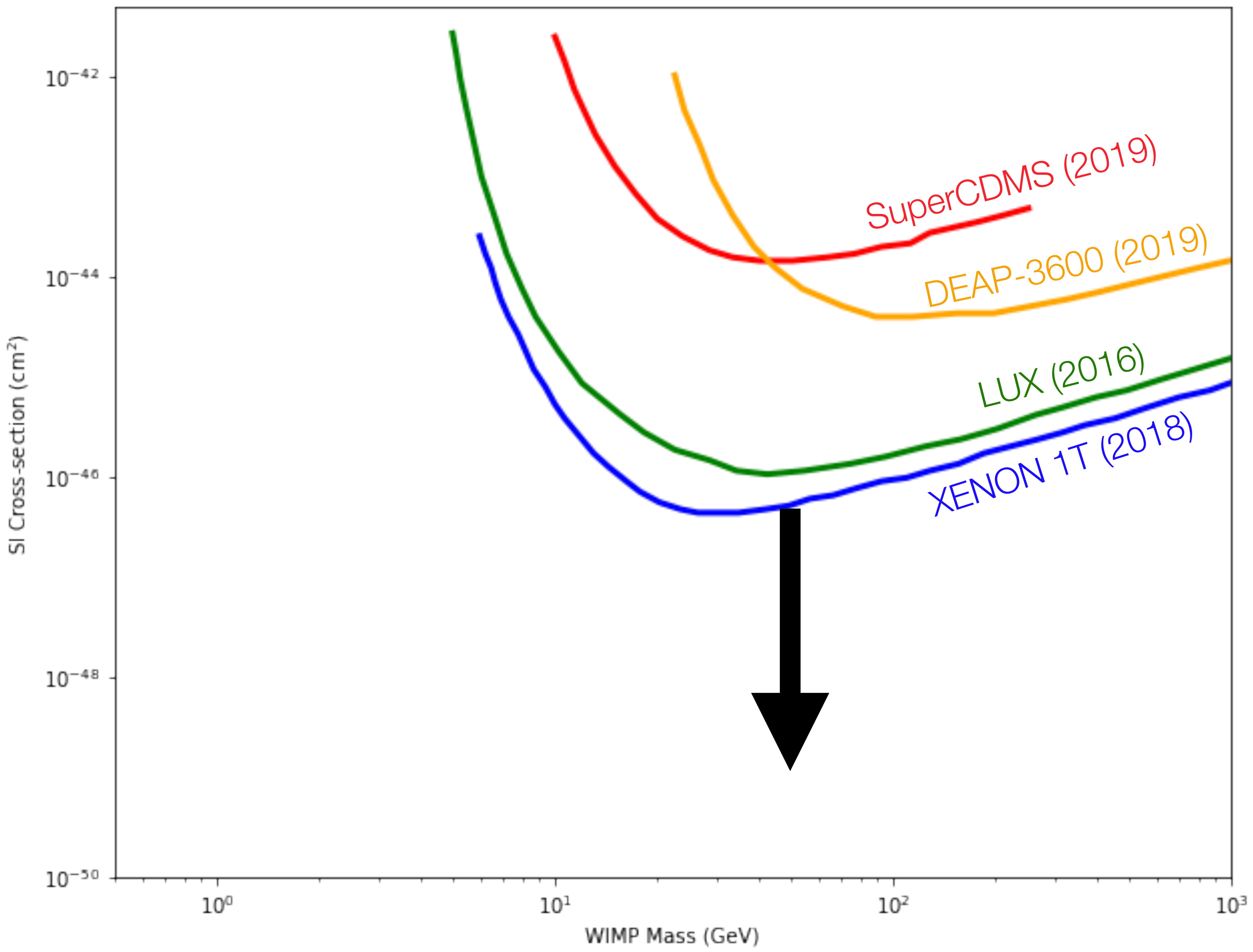


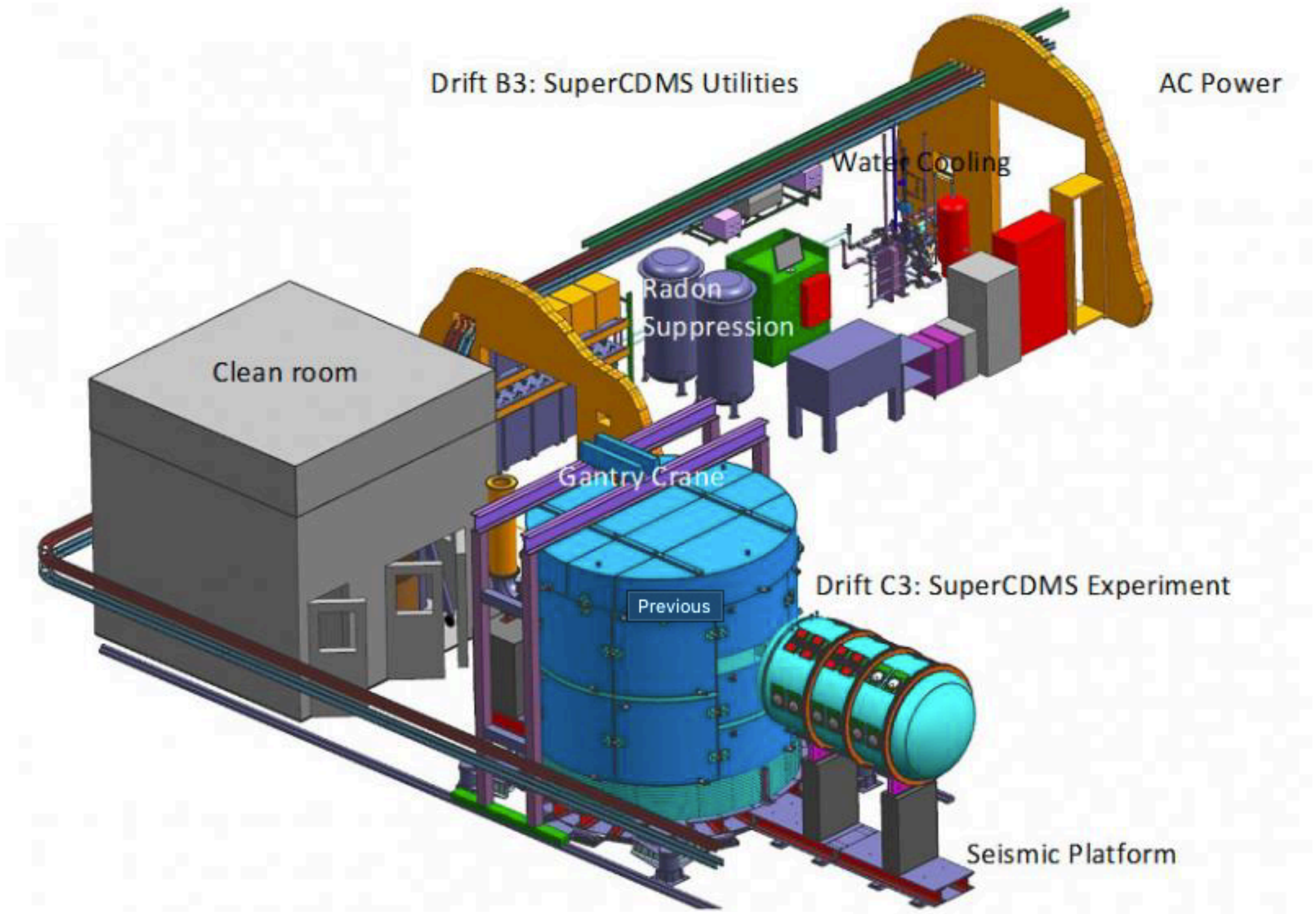
Phys. Rev. Lett. 116, 161302

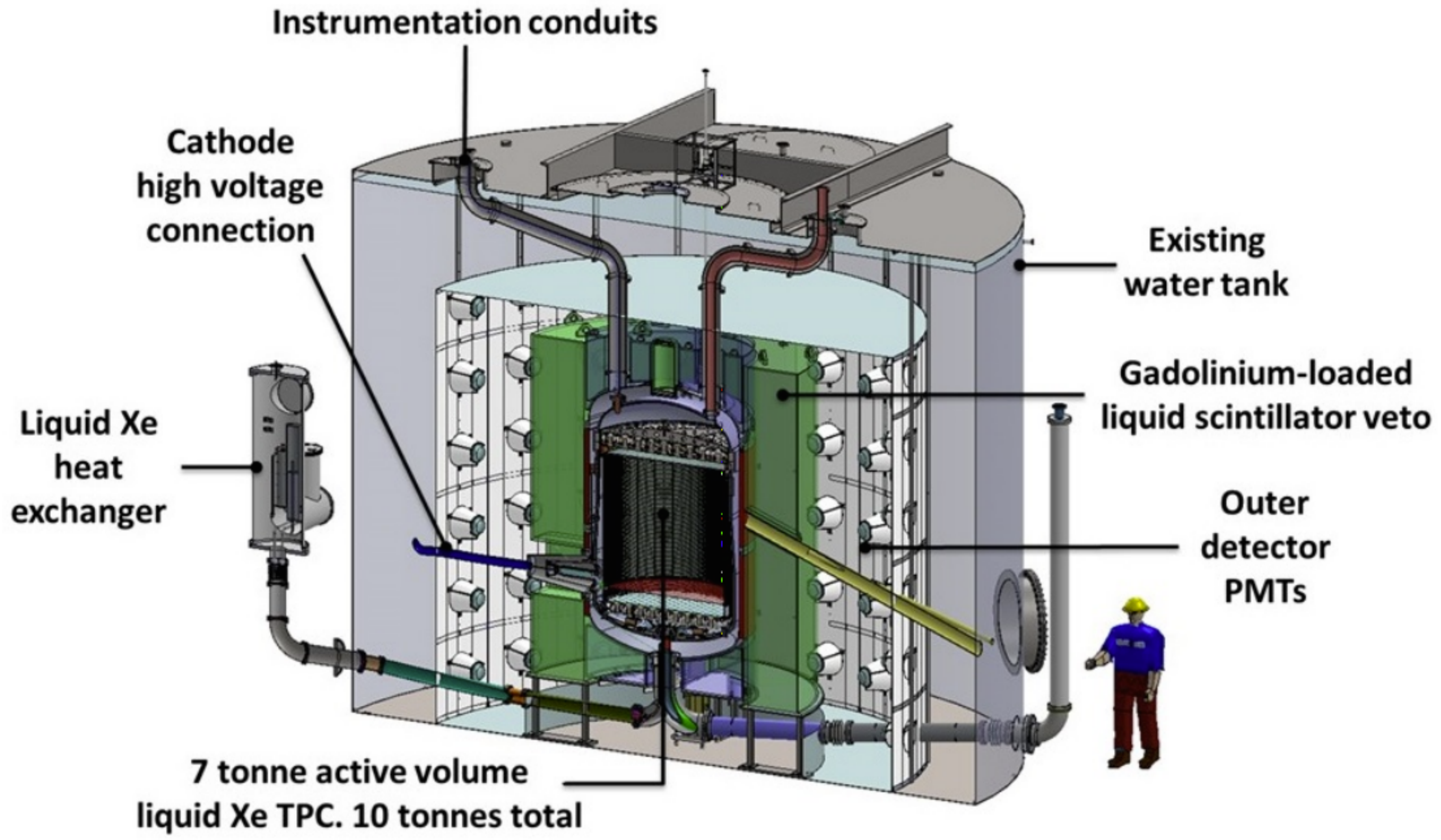
Where do we go now?

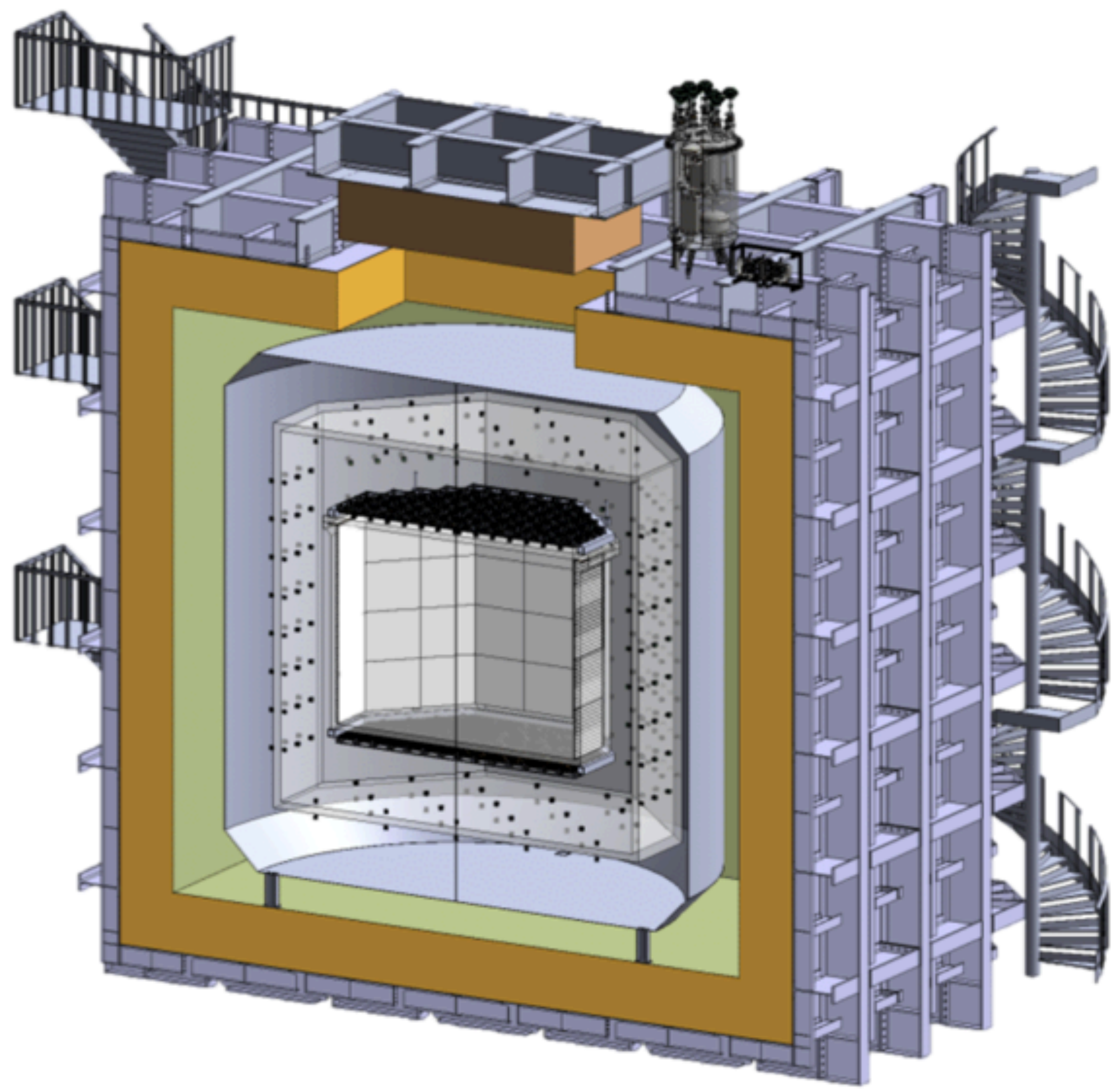
Queen's UNIVERSITY

How To Improve the Sensitivity

- The sensitivity scales with the exposure (target mass x time) so the plan generally is to get much larger



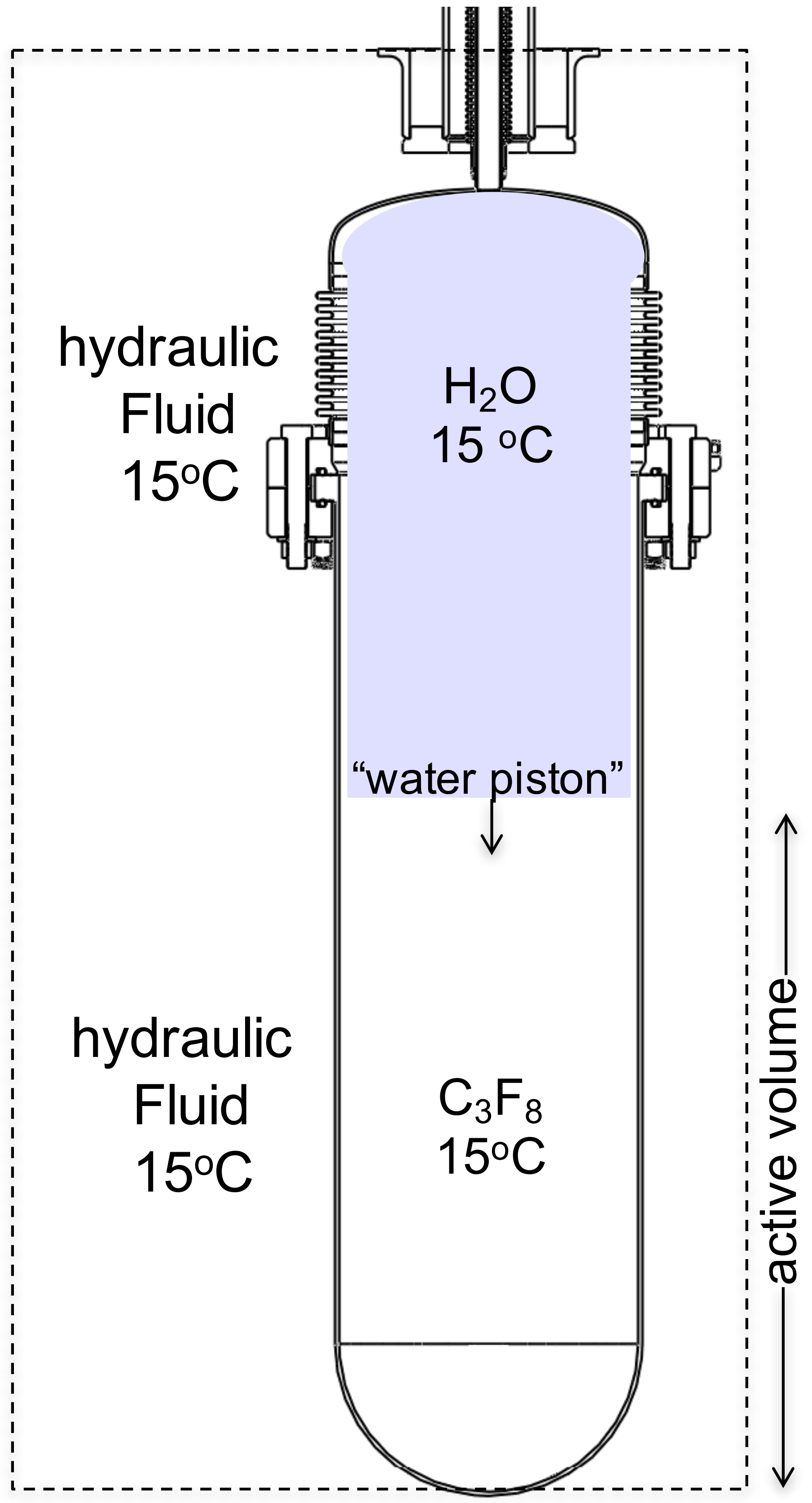




The Future of PICO

- Many problems seem connected to water/active fluid interface

PICO-60



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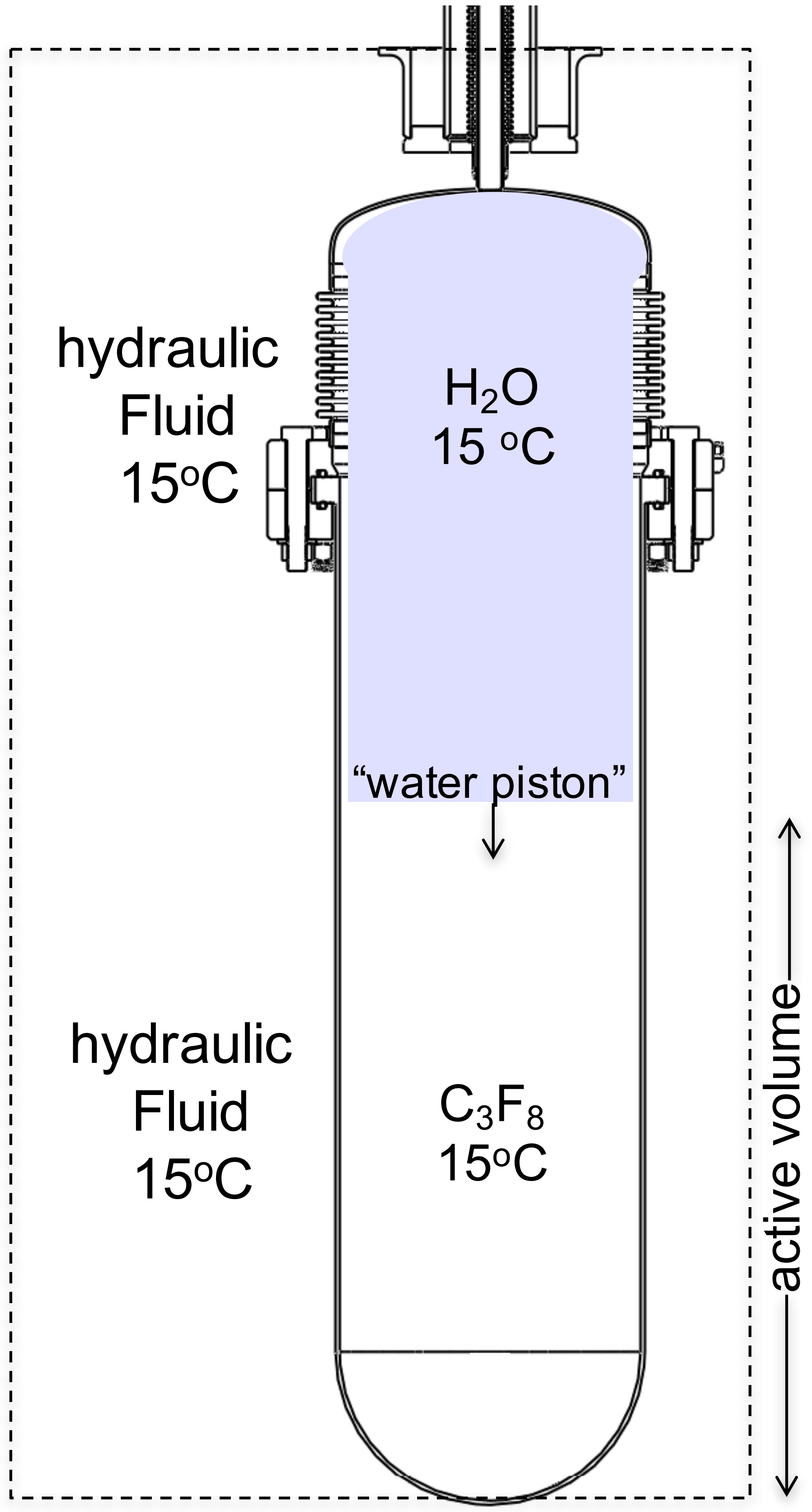
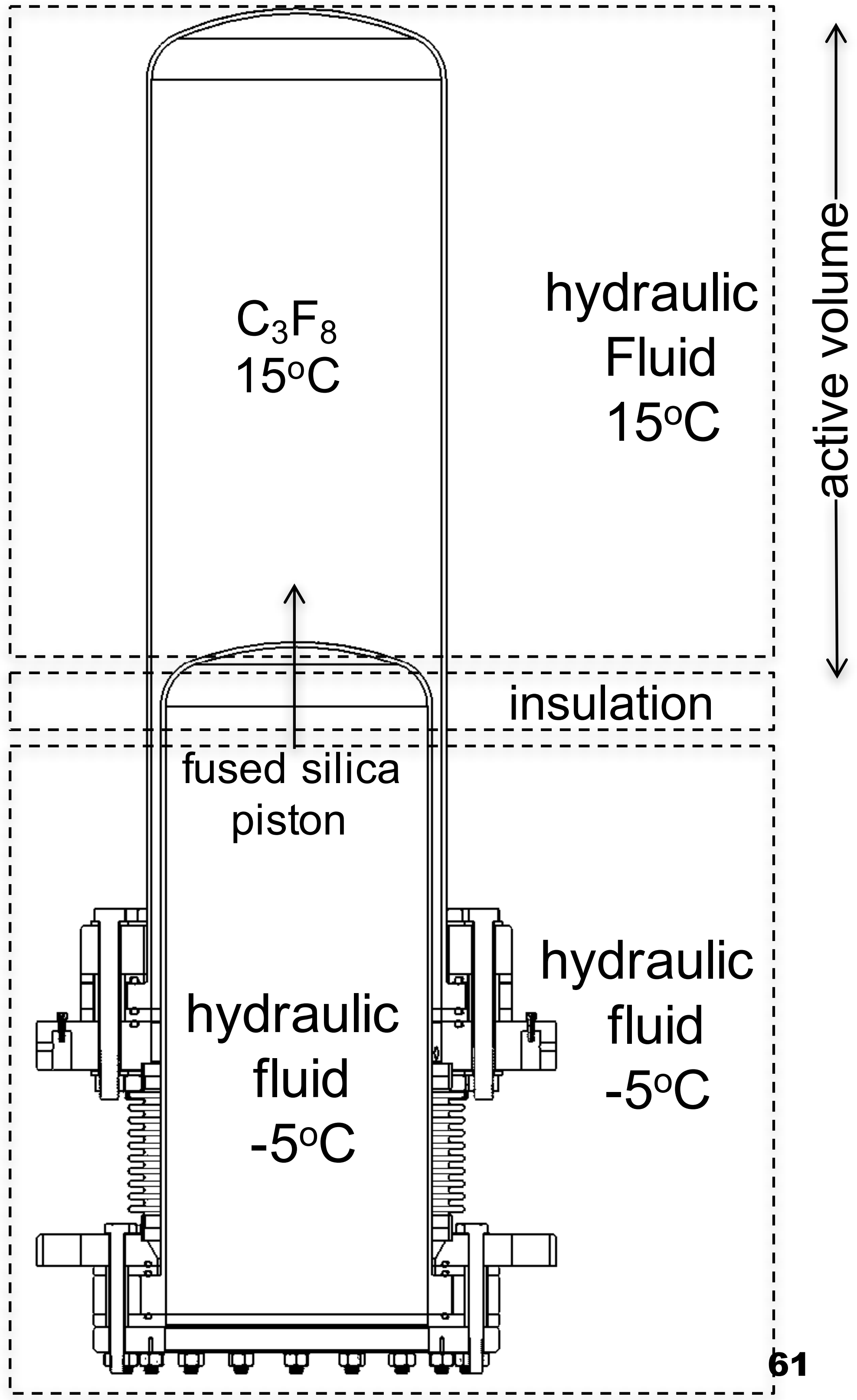
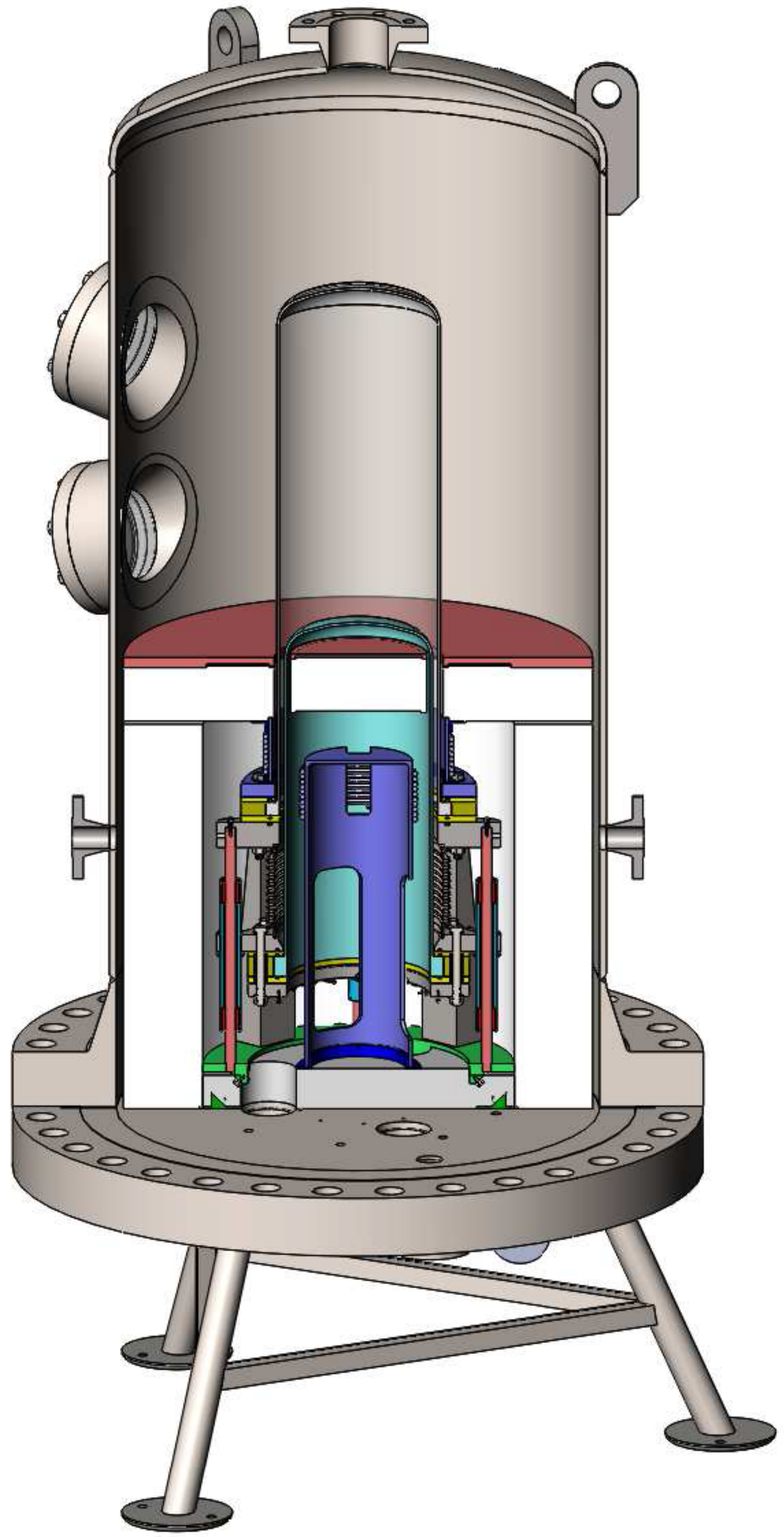




PICO-40L

PICO 40L

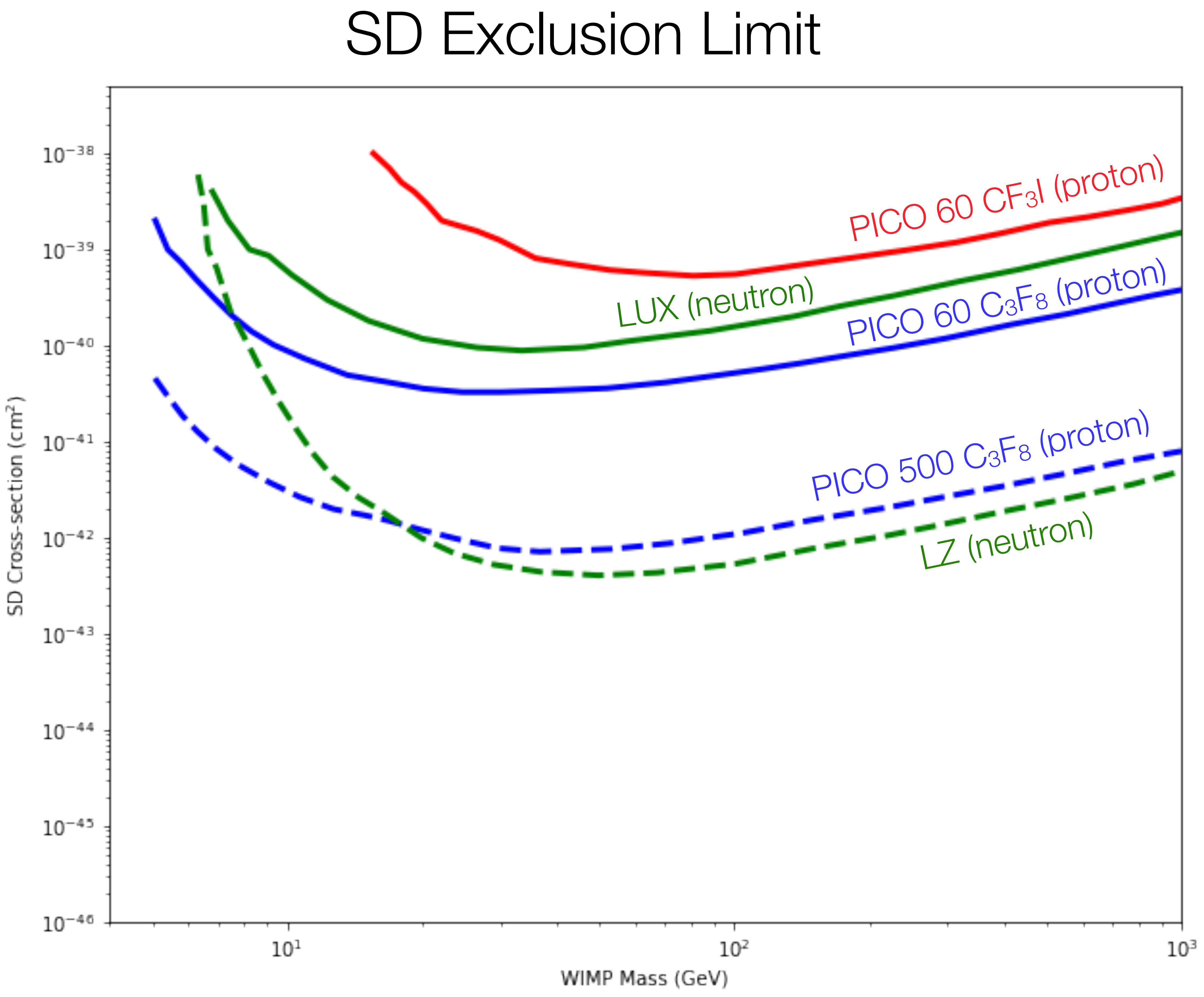
- “Flips” the sensitive volume to remove water buffer fluid
- Constructed underground at SNOLAB
- Commissioning underway, dark matter data taking to begin shortly

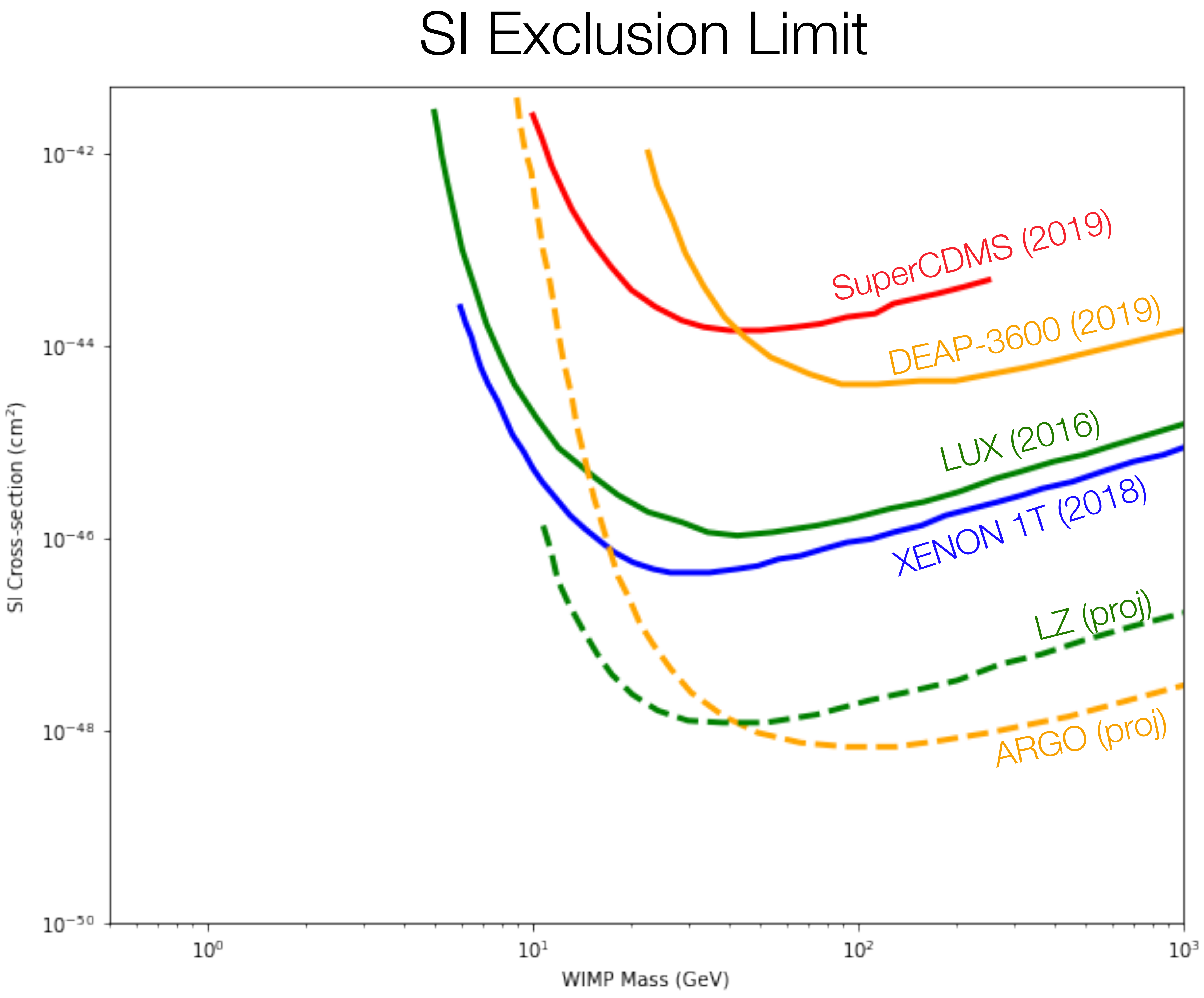


The Further Future

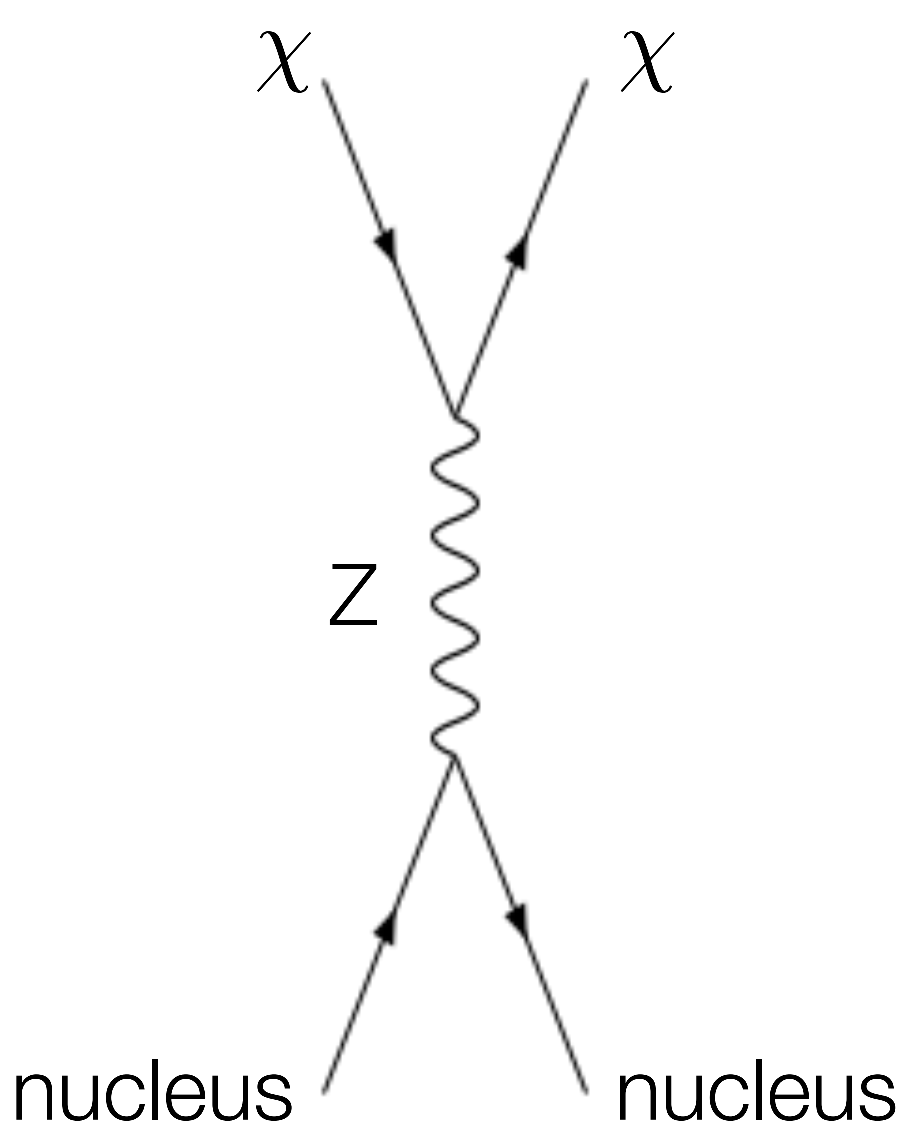
- Increasing from PICO 40 to PICO 500
- Design currently underway

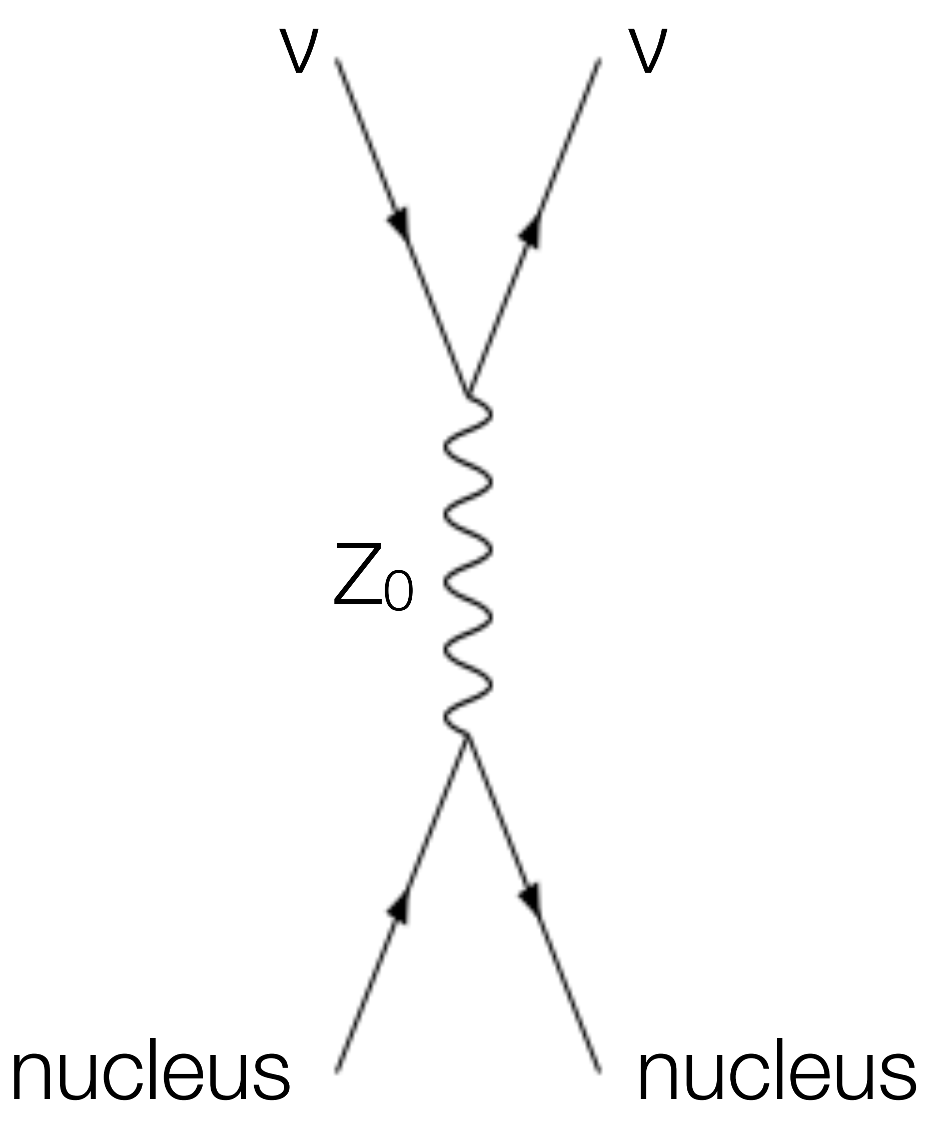
State of Experiments





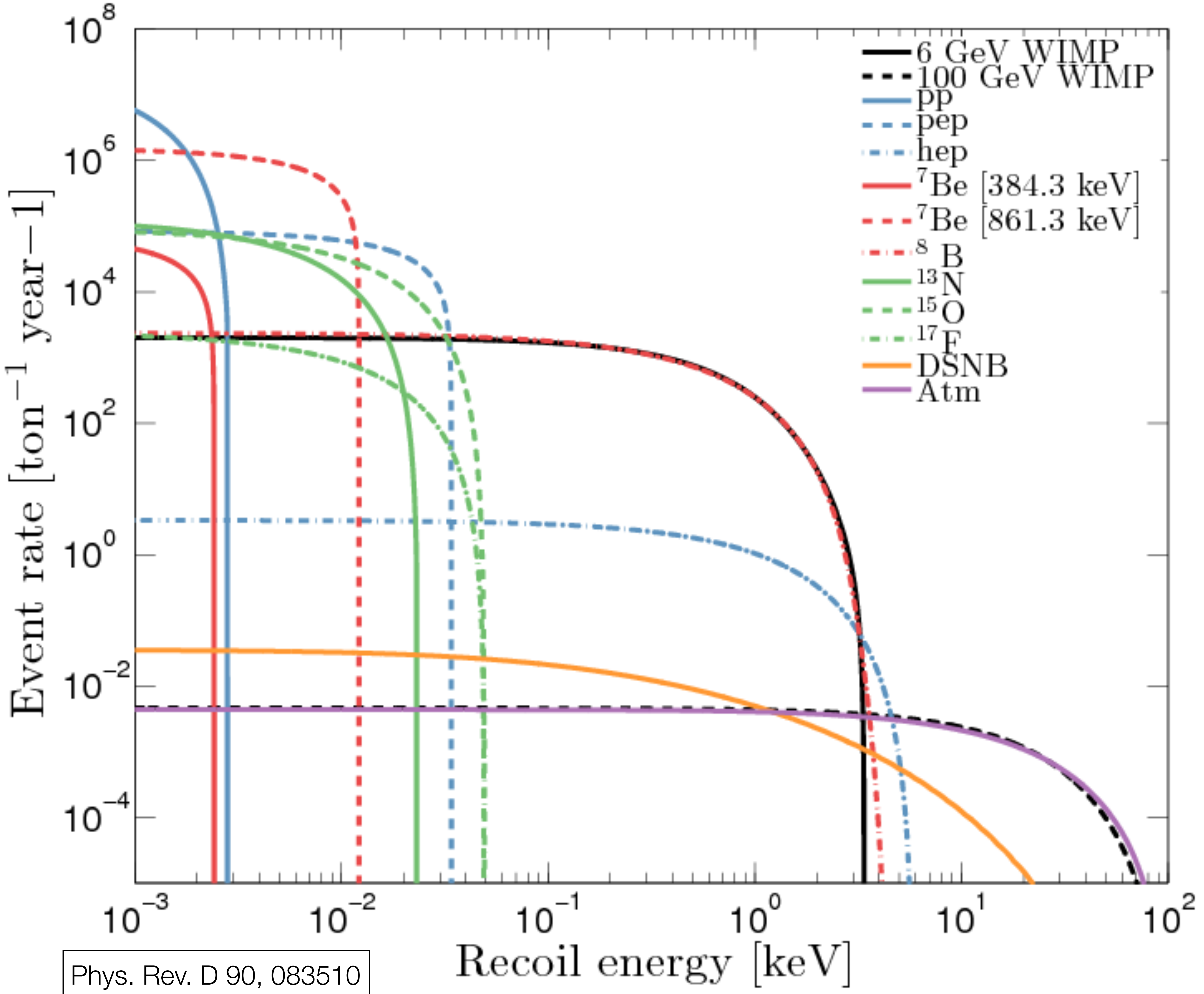
The Problem on the Horizon





- Observed coherent elastic scattering of neutrinos
- Insensitive to neutrino flavour, occurs at small cross-sections

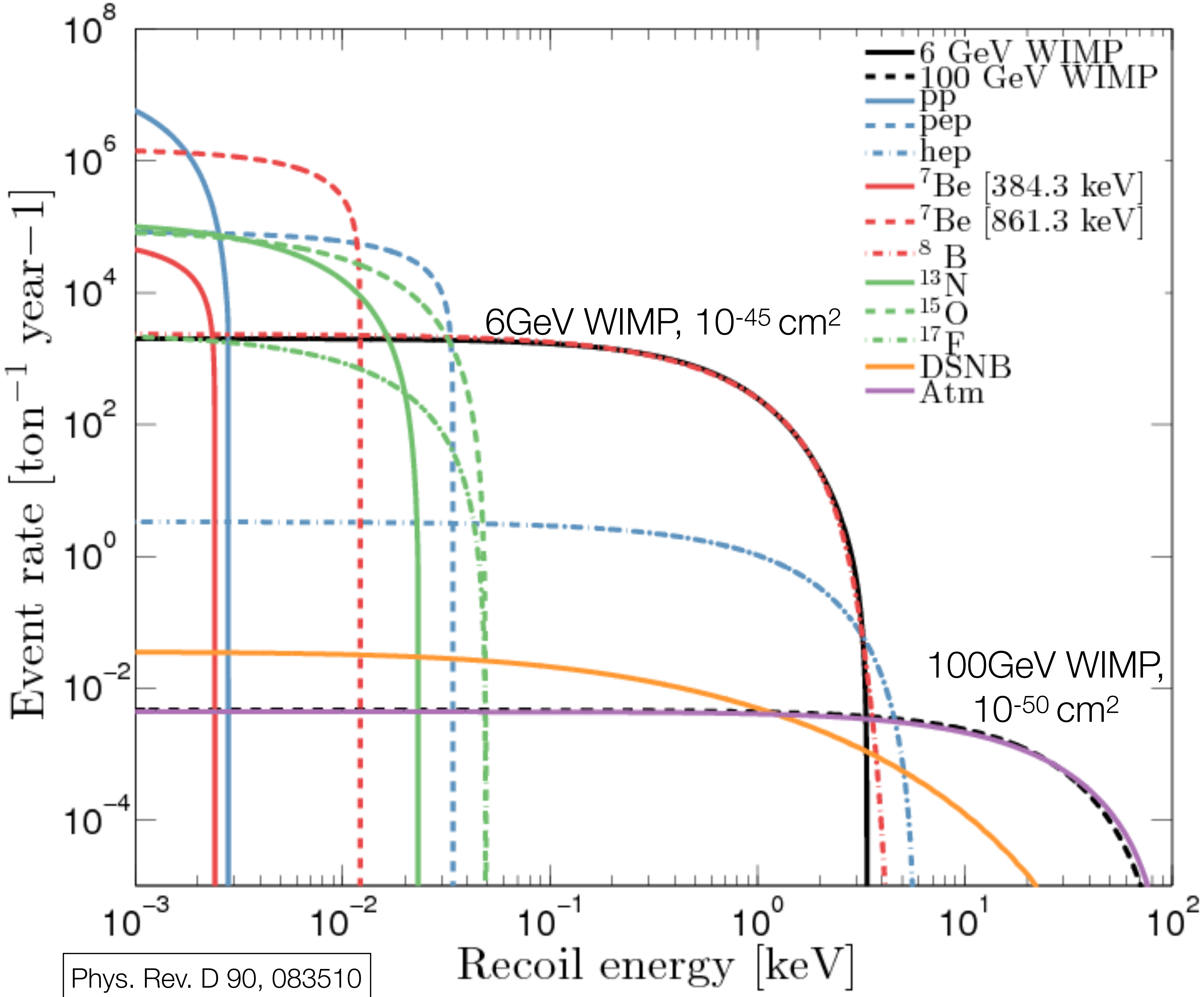
But This is Very Rare, right?



Phys. Rev. D 90, 083510

- These rates look bad, but the WIMP cross-sections are far below our range…?

But This is Very Rare, right?



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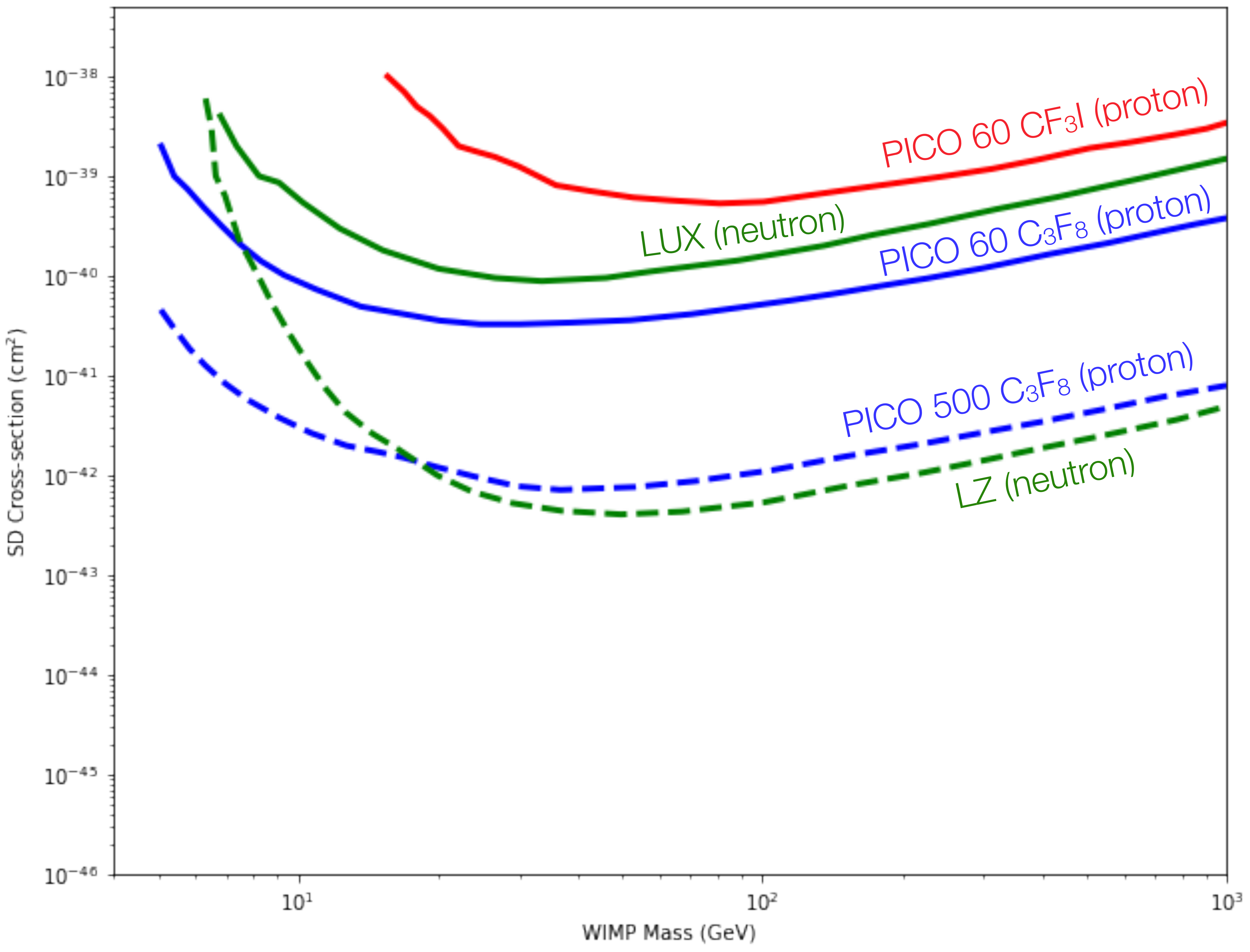
The Future!

SD Exclusion Limit



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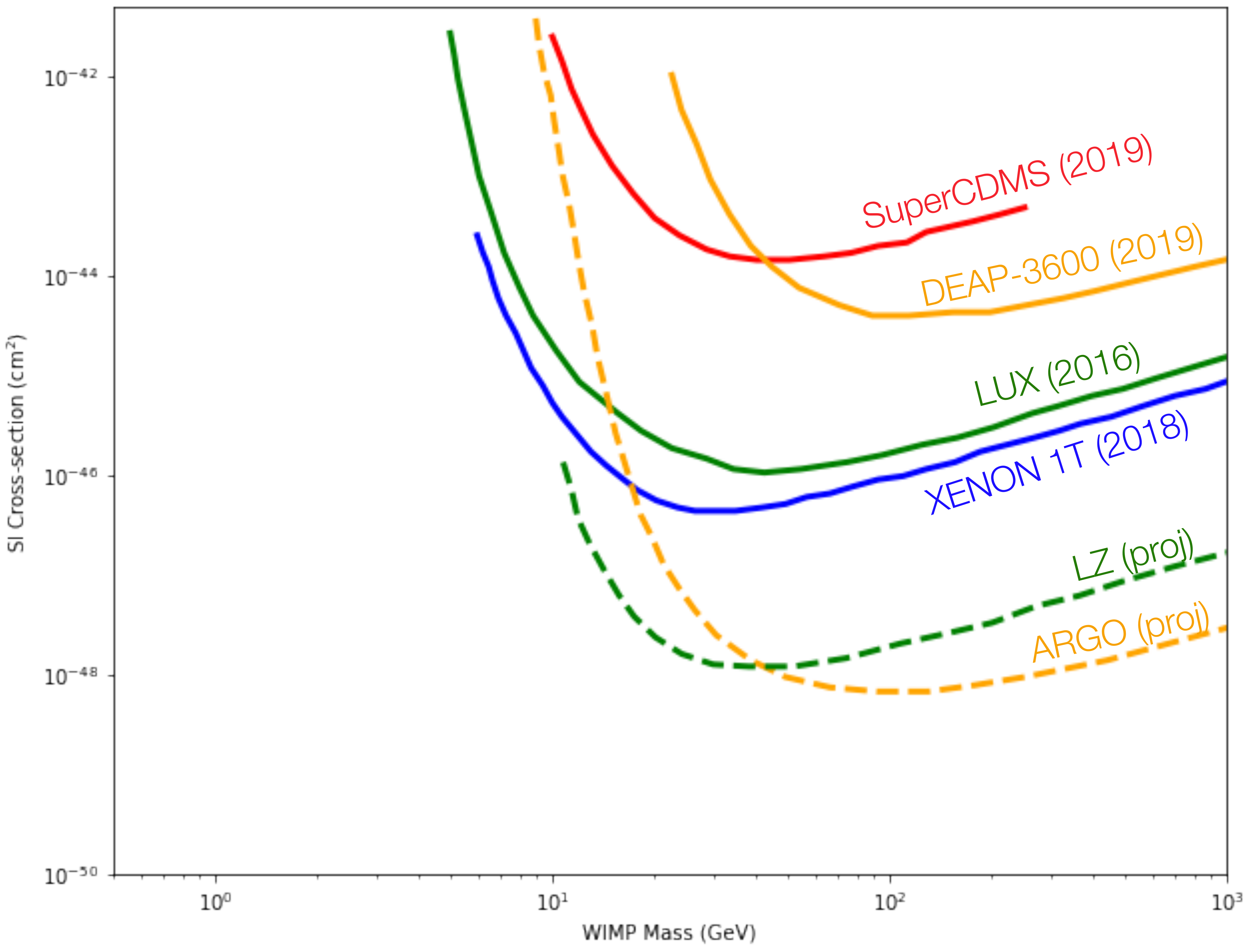

The Future!

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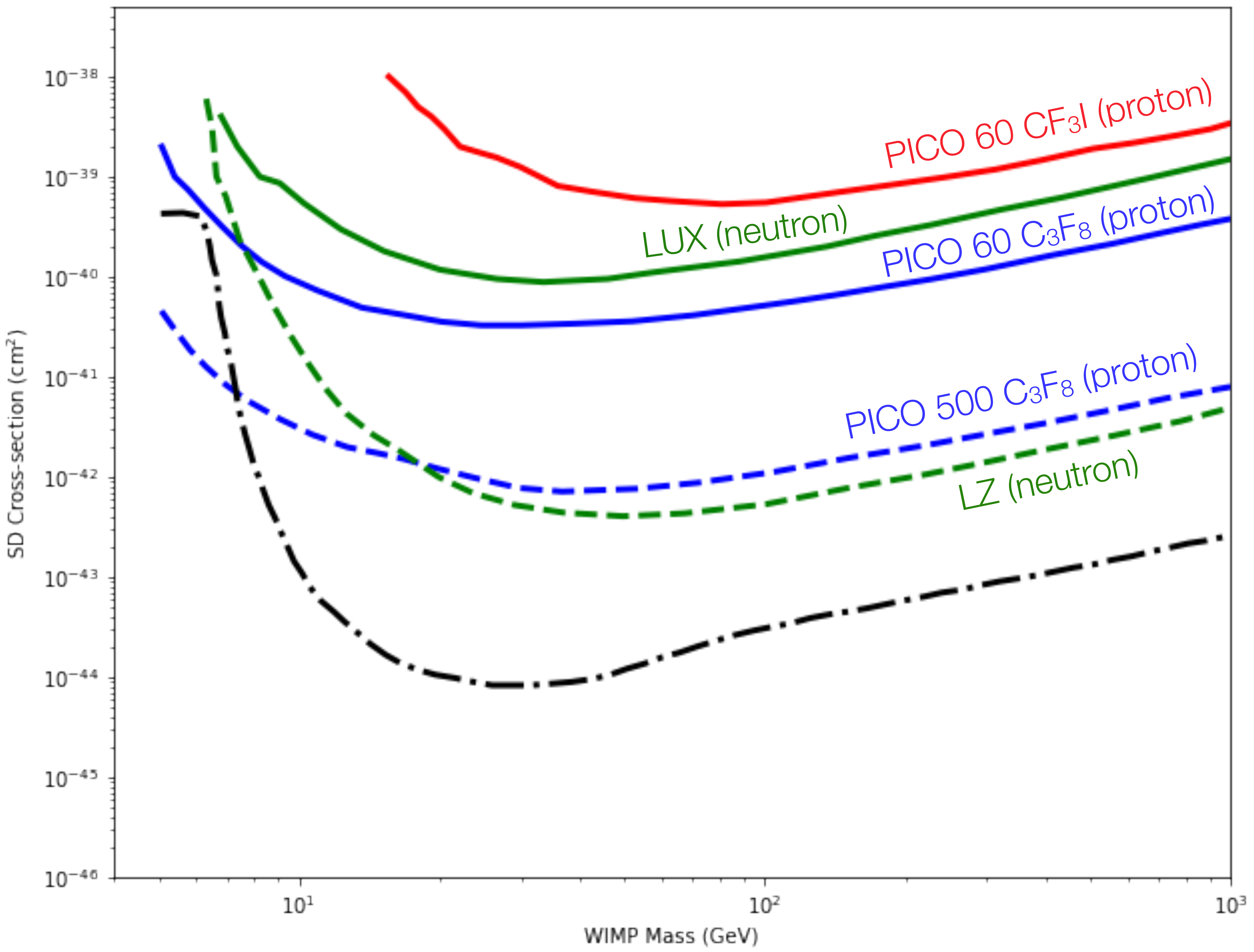

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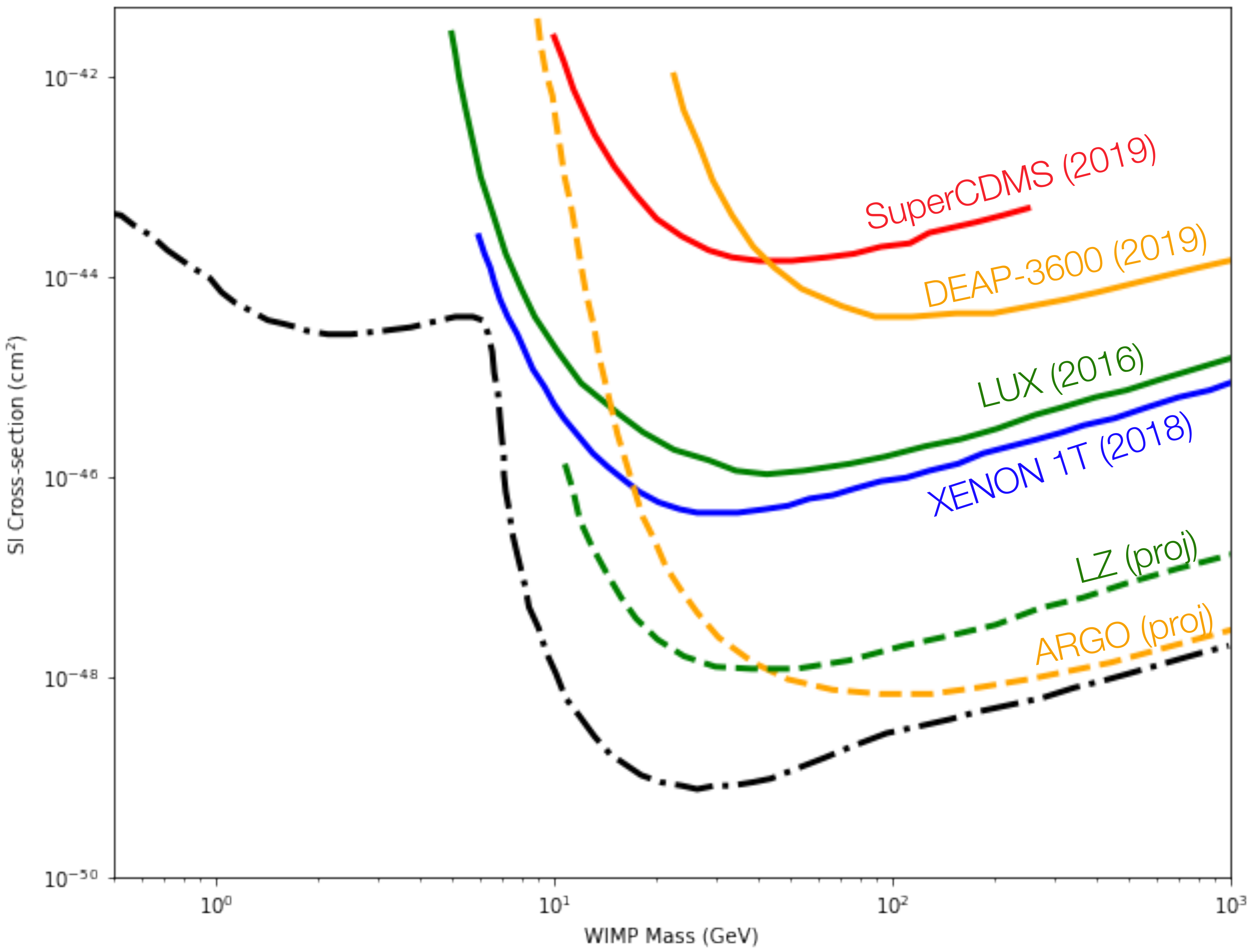
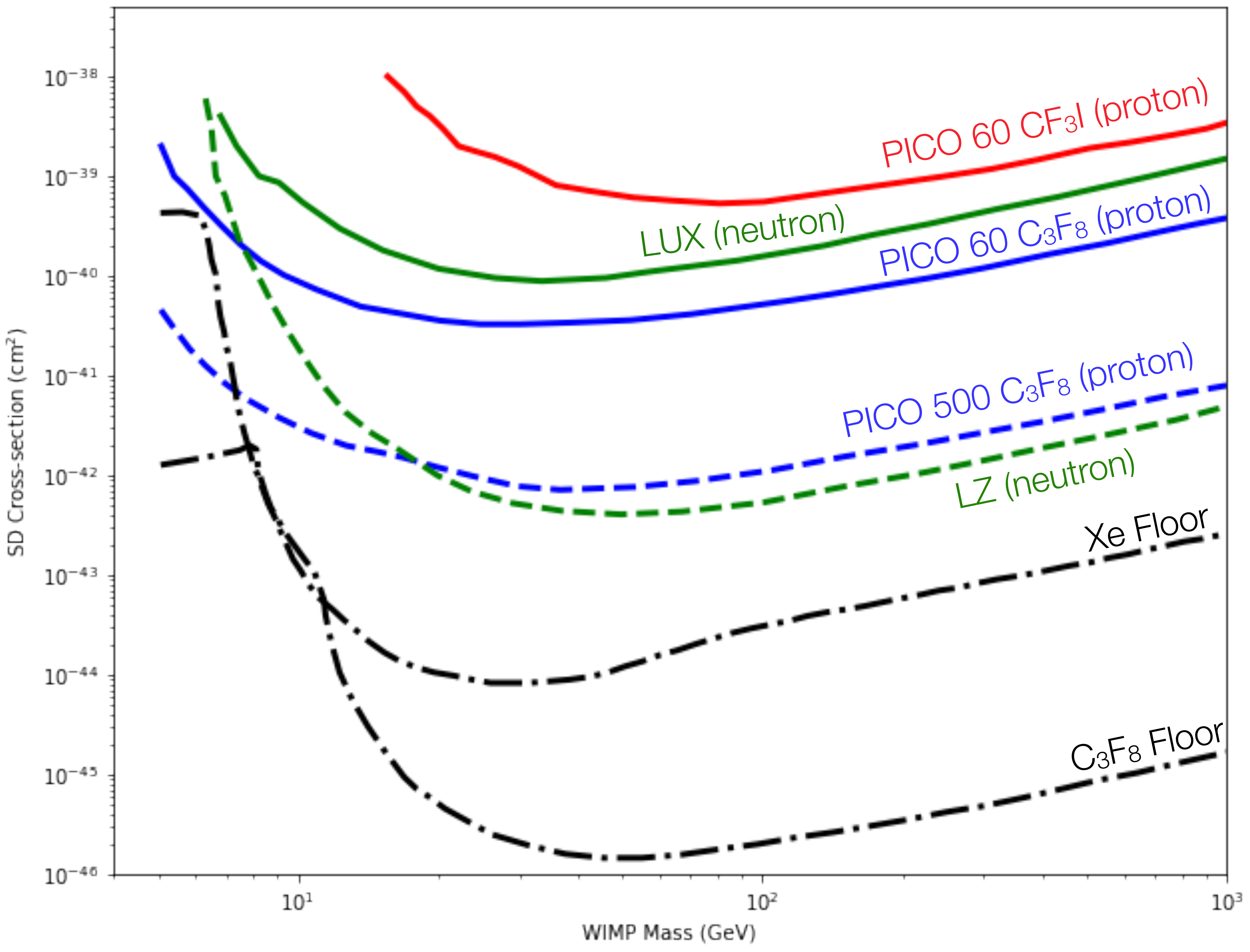


Neutrino Floors: Phys. Rev. D 90, 083510

The Floor is not THE Floor

SD Exclusion Limit



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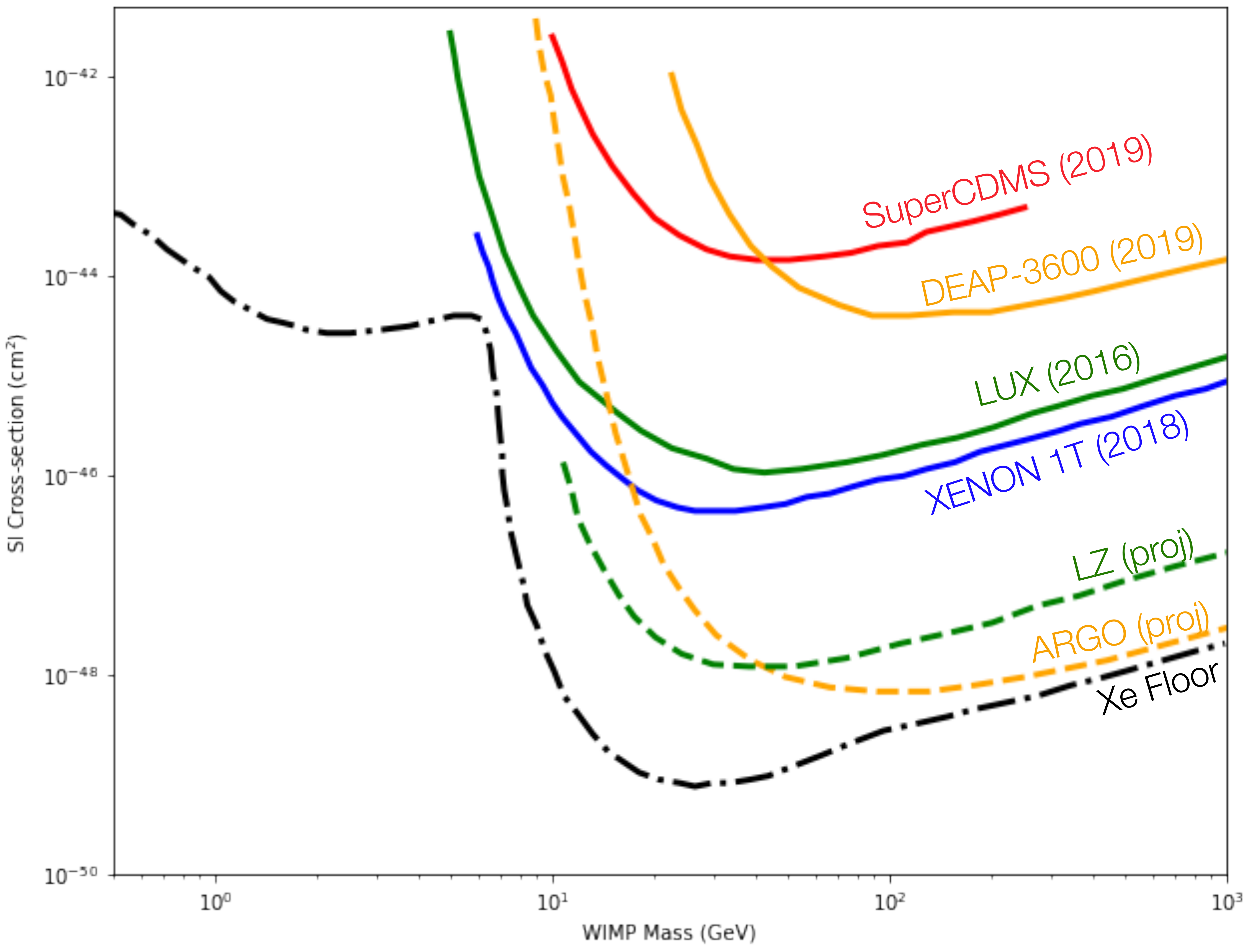
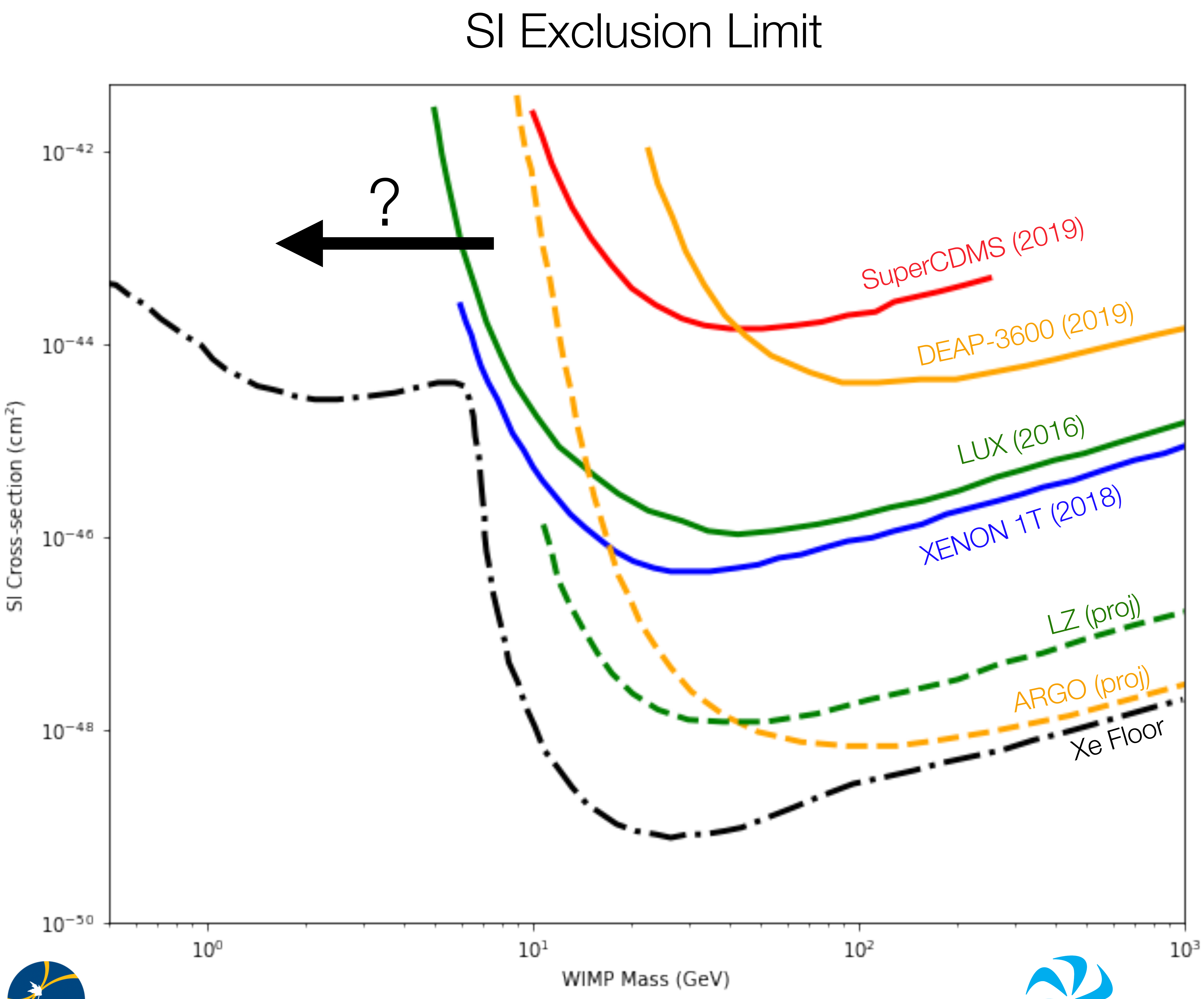


Neutrino Floors: Phys. Rev. D 90, 083510

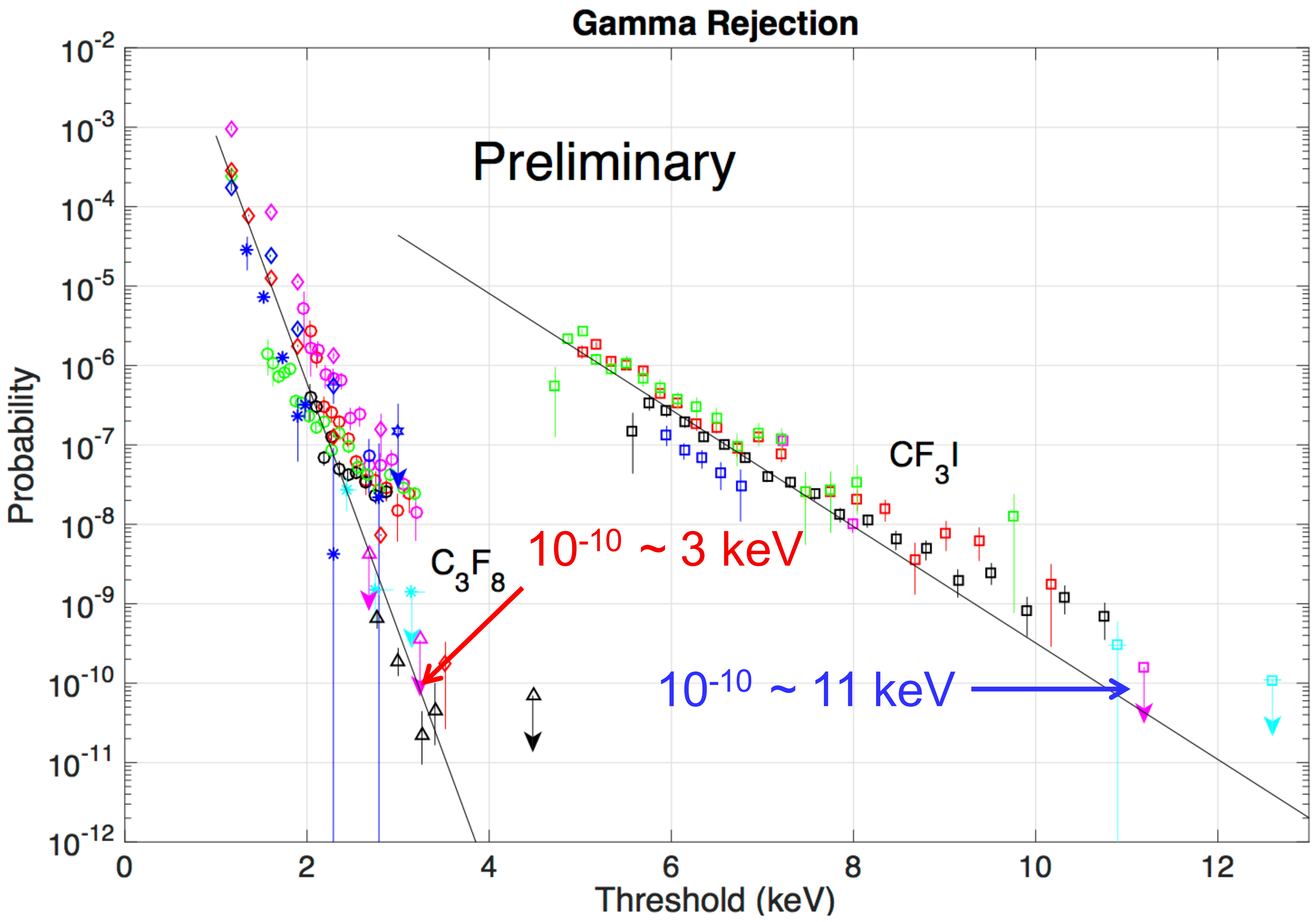
Side note: Is this the only direction?



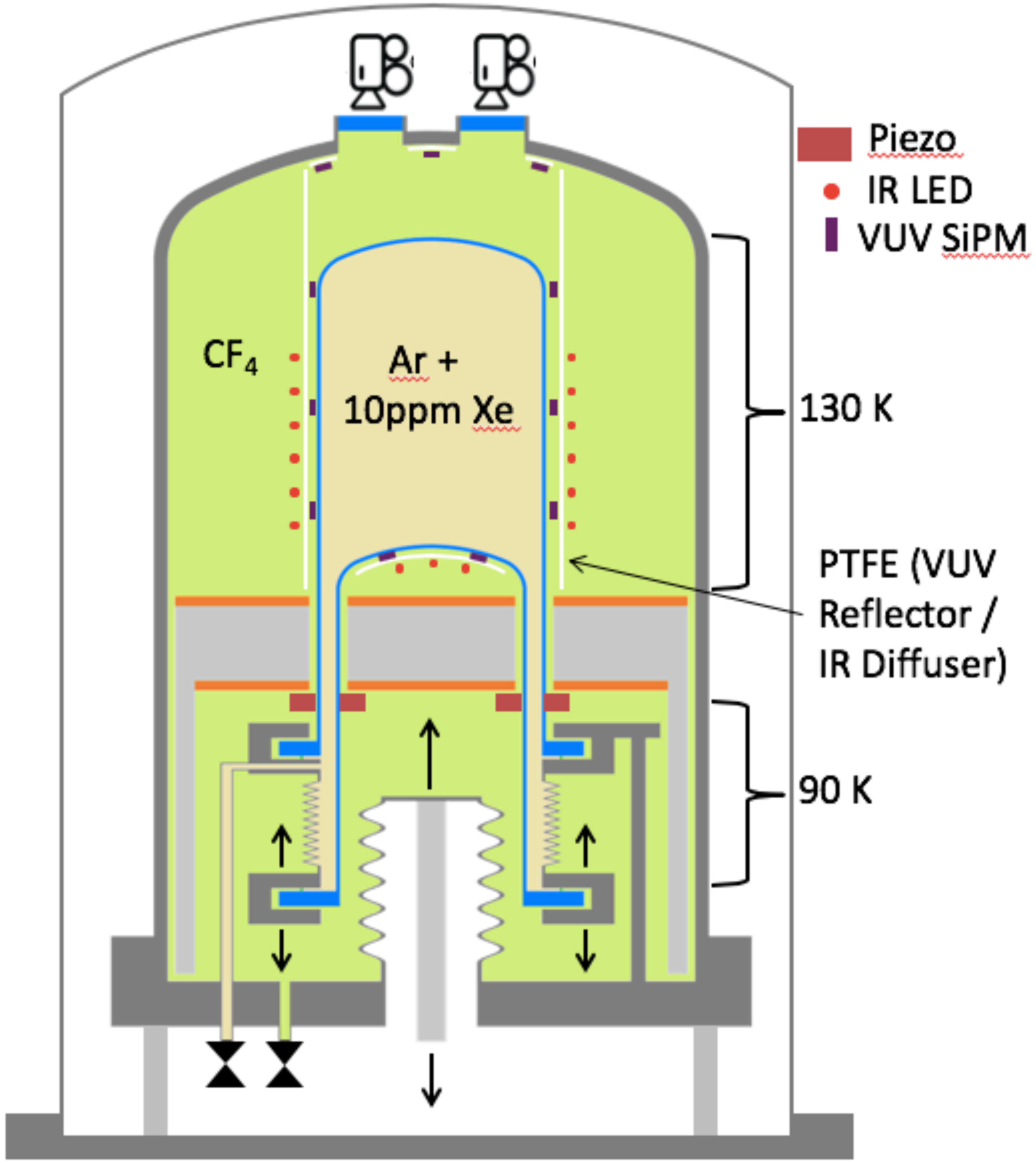
- Should we just get bigger and try to hit the floor?
- There is still low mass area to be investigated
- Getting into this space requires low threshold and potentially different techniques

A New(ish) Technique!

- PICO works very well, but the threshold can't be set low due to gamma interactions



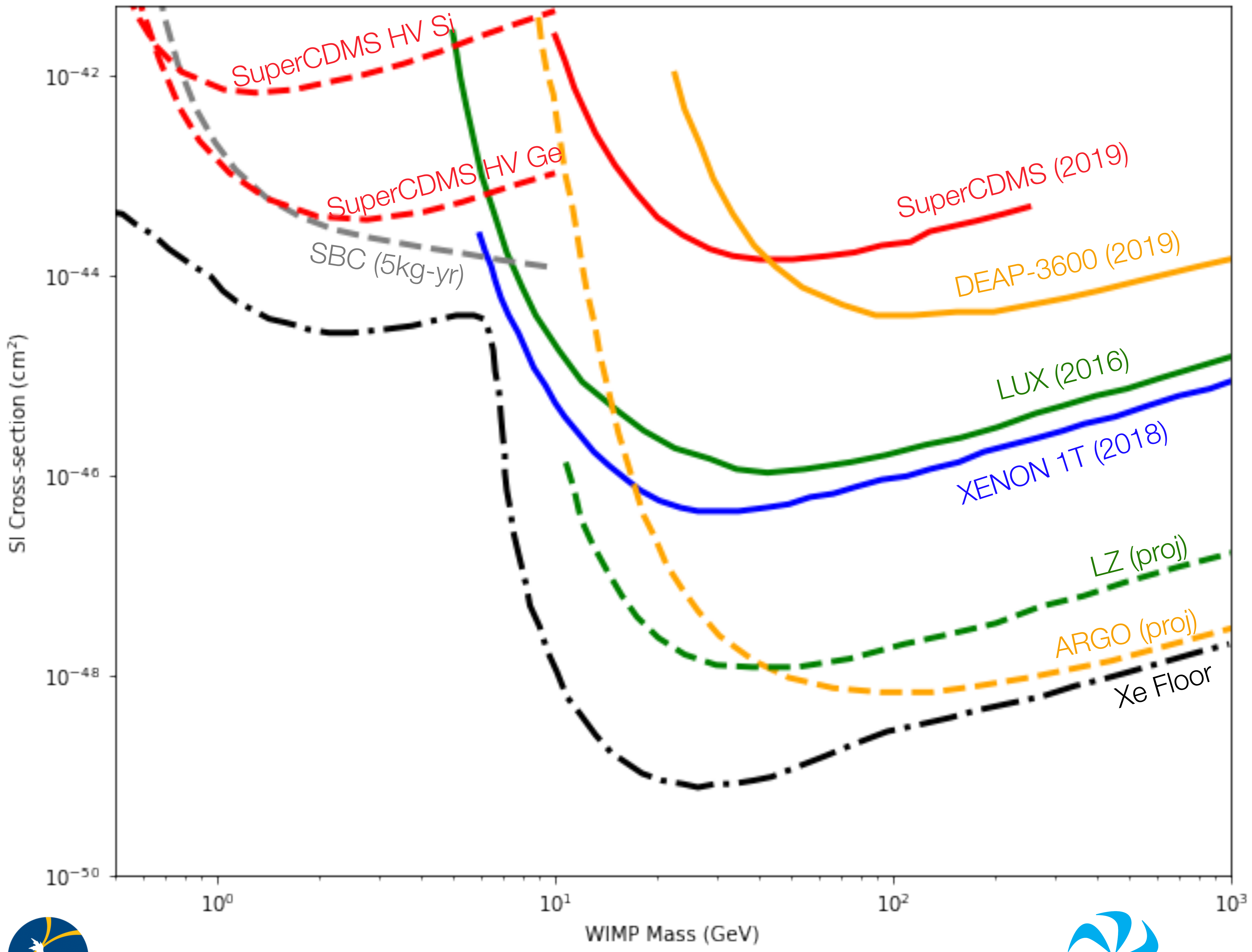
A New(ish) Technique!



- Replace the C3F8 with Argon (and some xenon)
- Scintillation inhibits bubble formation for backgrounds
- Currently under construction, installation at SNOLAB in 2021

Low Mass Exploration

SI Exclusion Limit

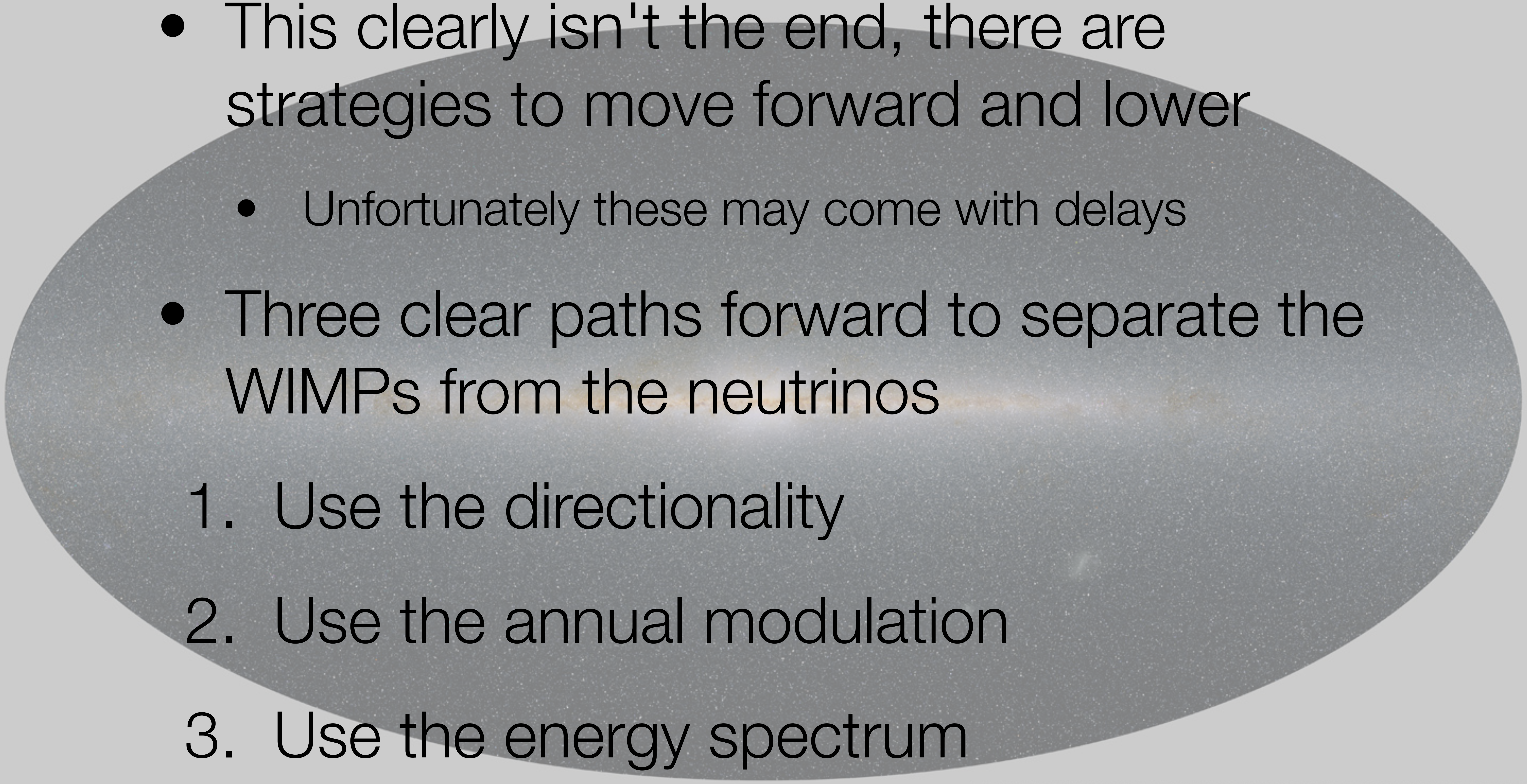


- Should we just get bigger and try to hit the floor?
- There is still low mass area to be investigated
- Getting into this space requires low threshold and potentially different techniques

So where do we go from here?

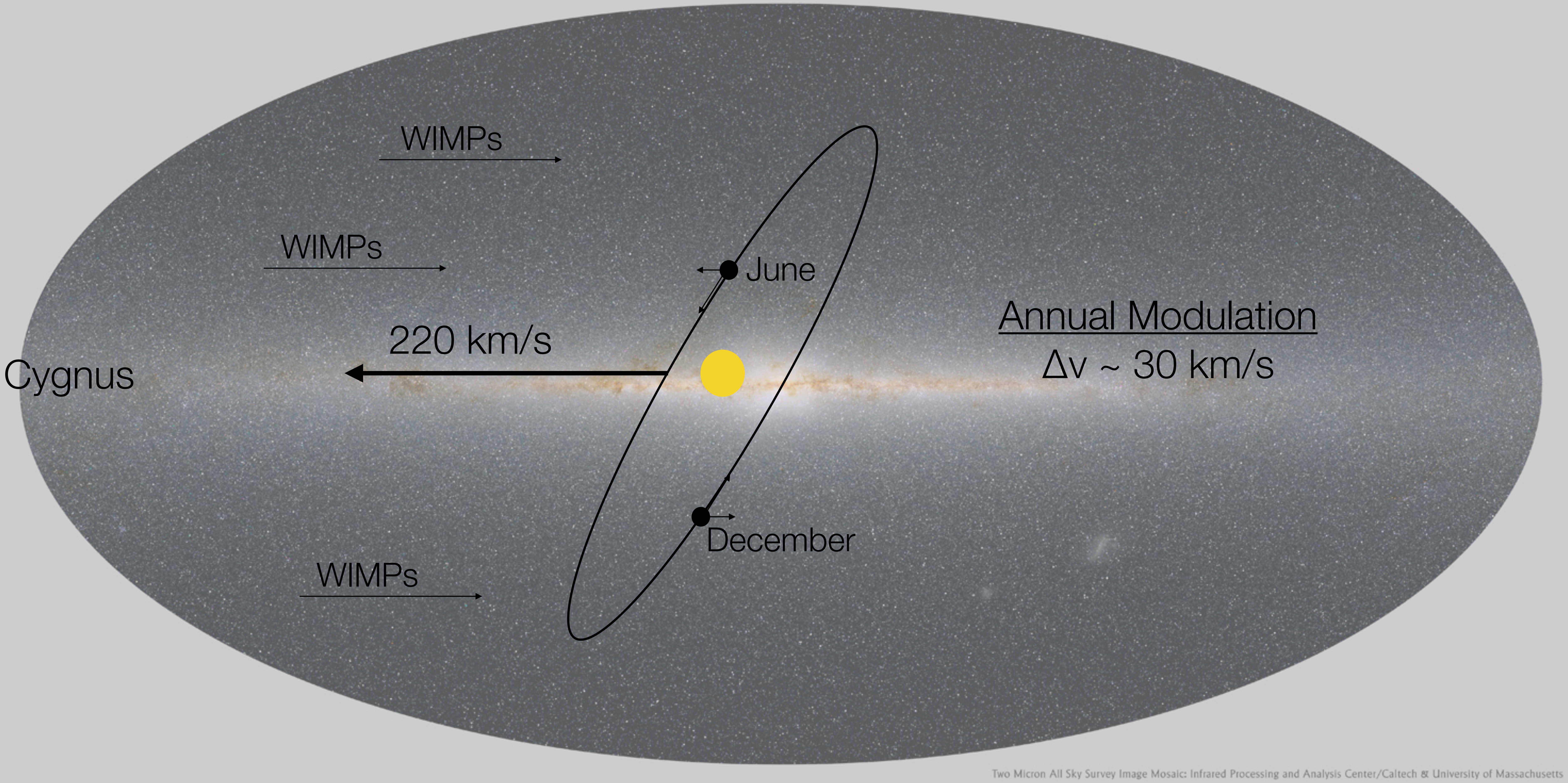
- This clearly isn't the end, there are strategies to move forward and lower
  - Unfortunately these may come with delays
- Three clear paths forward to separate the WIMPs from the neutrinos

1. Use the directionality
2. Use the annual modulation
3. Use the energy spectrum

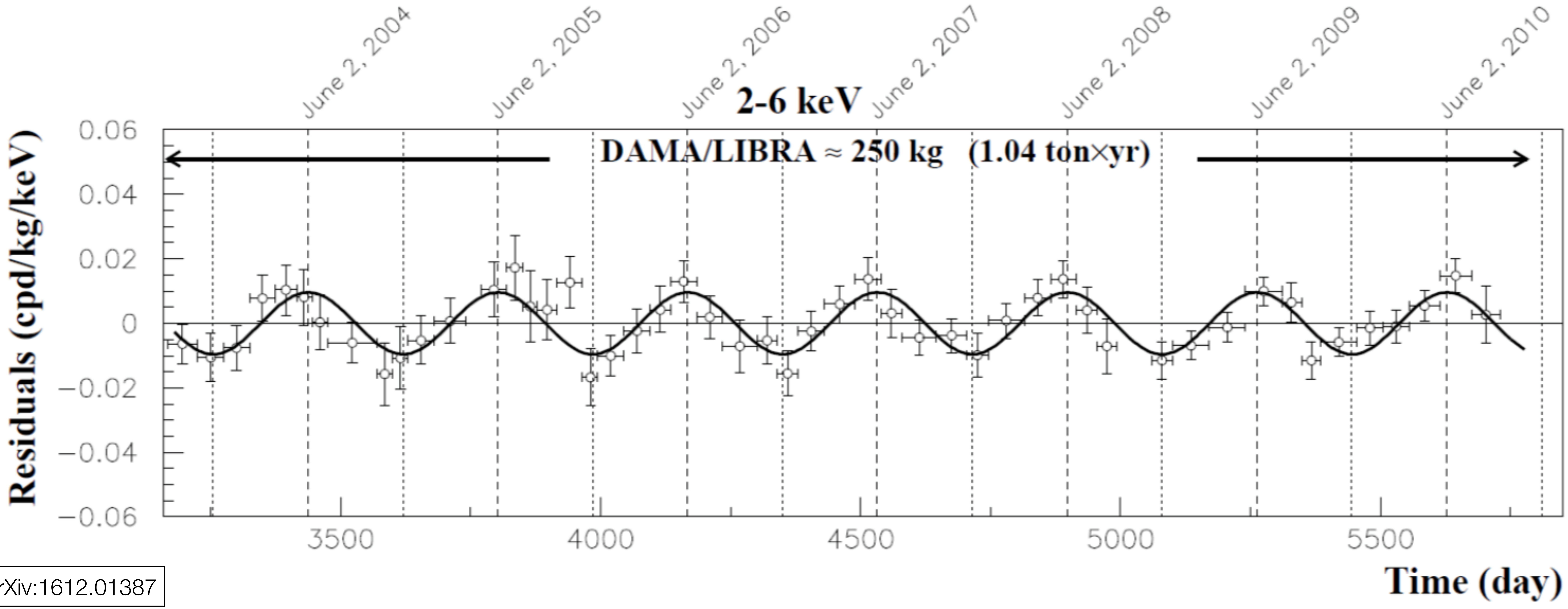


Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Directionality & Modulation



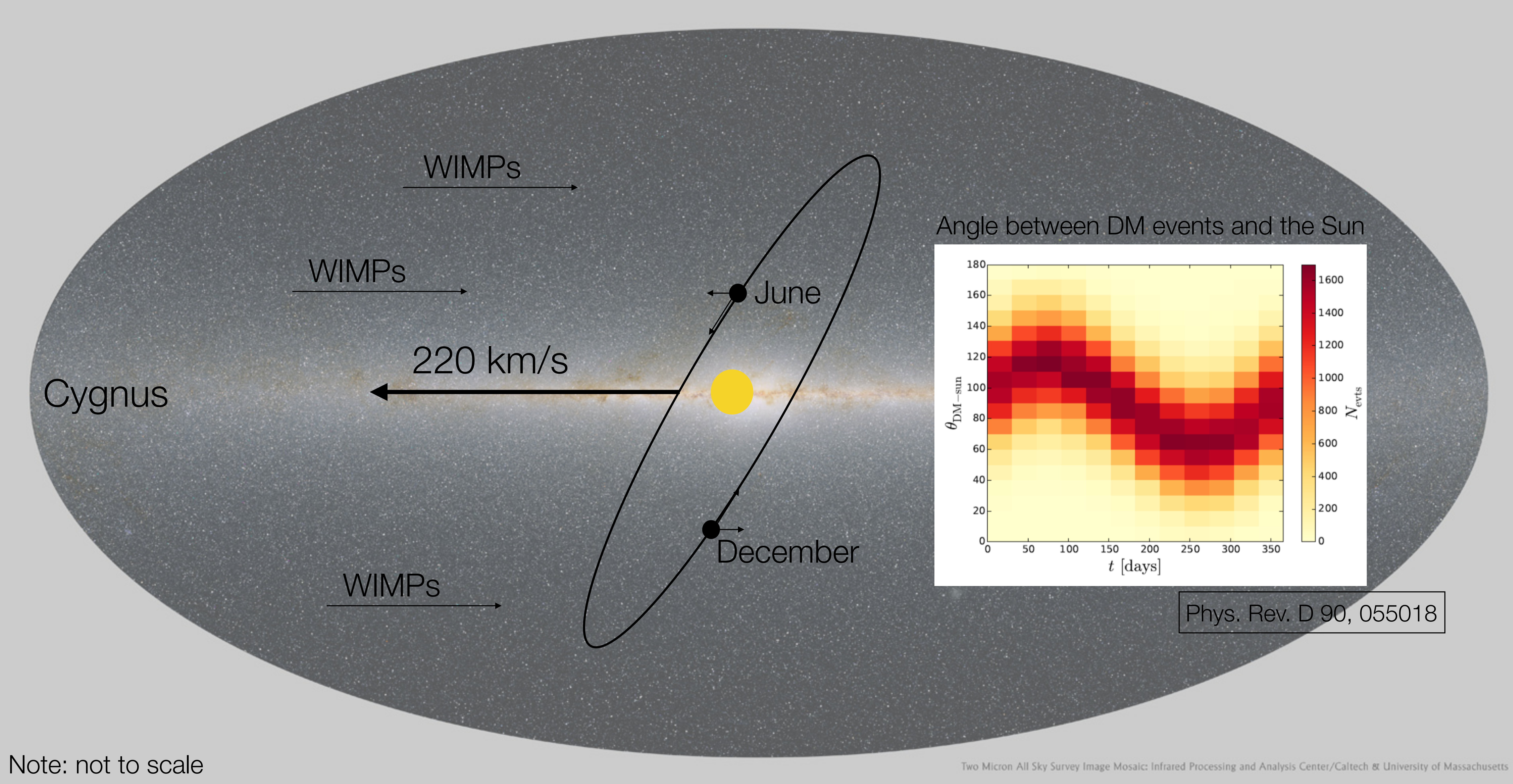
Detection?



arXiv:1612.01387

- Annual modulation clearly detectable in any dark matter experiment
  - Requires YEARS of data, however

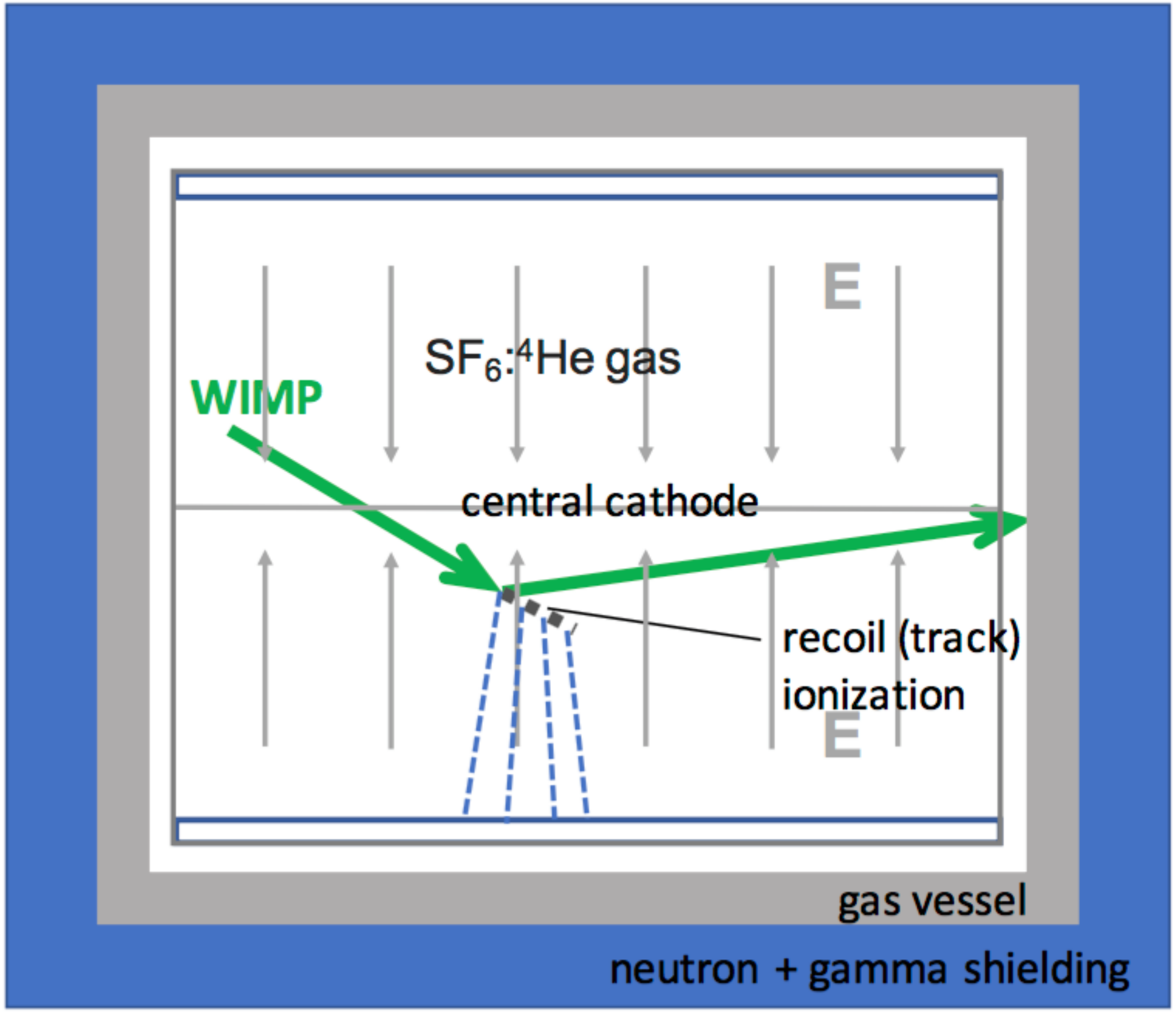
Directionality & Modulation



Note: not to scale

Requires new Detector Technology

- Difficult to increase to competitive size, but that technology is coming
- The CYGNUS HD10 detector is one example



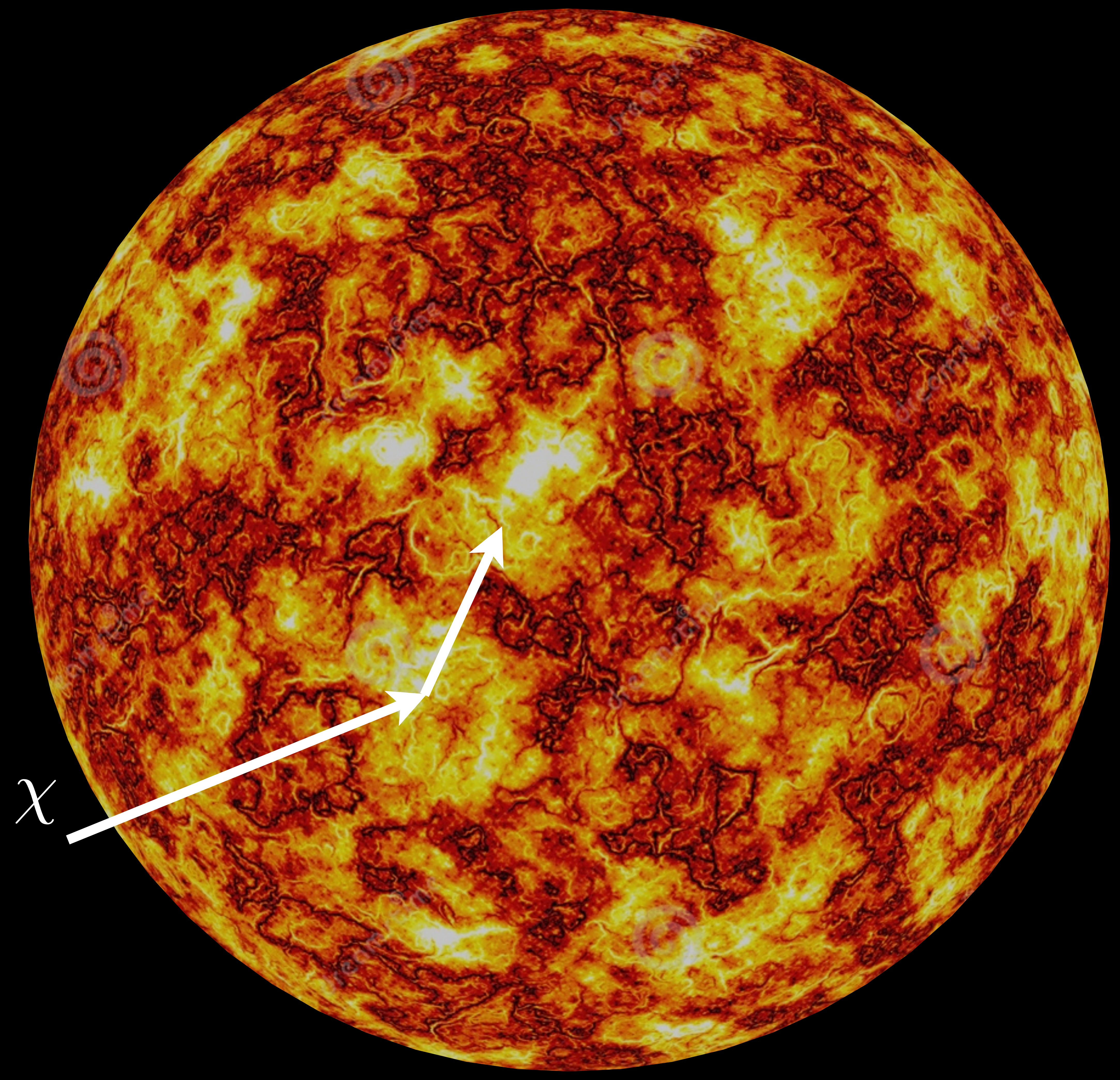
Example detector

Is There Another Way?

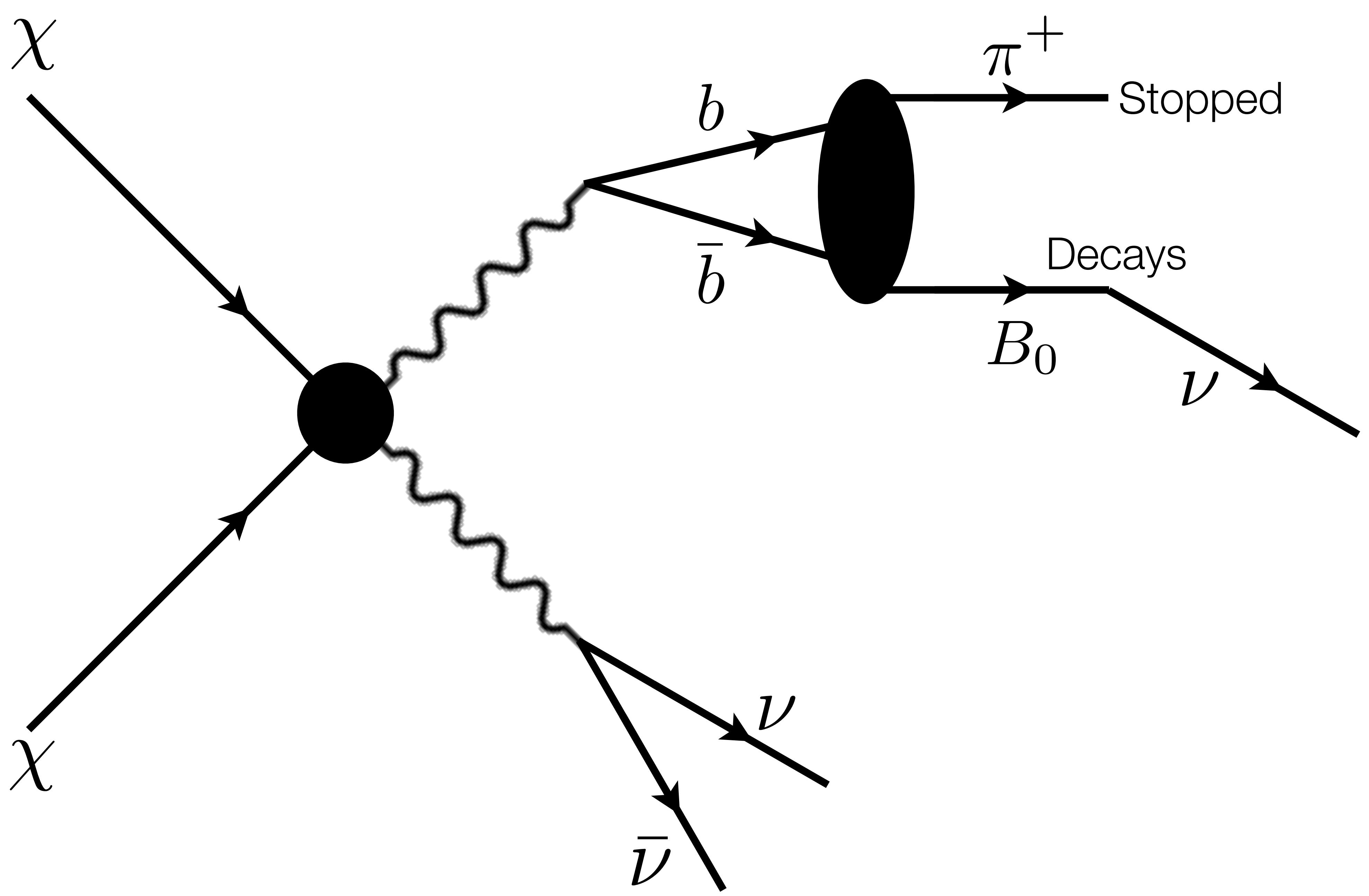
- Earlier said that we would exploit the properties of the dark matter to find it
- One of the potential properties was the ability of dark matter to interact non-gravitationally with itself
- Can we use this to hunt it?

Indirect Detection

- Several experiments looking for signals from dark matter annihilation
- Large masses will collect dark matter particles through scattering and capture
- Scattering here is the same process used by the direct detection experiments

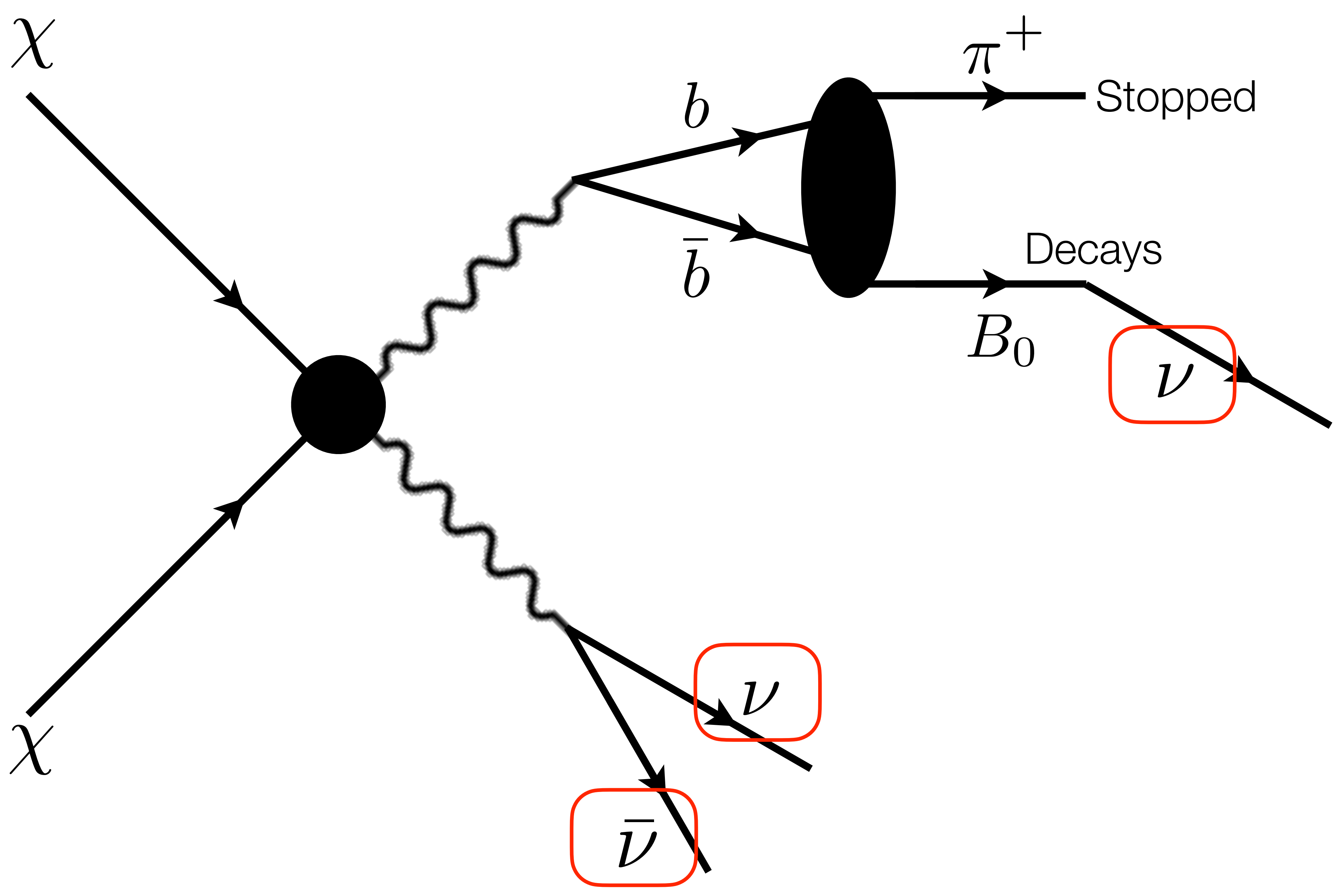


Dark Matter Annihilation



- Assuming the DM is a Majorana particle, it will self-annihilate in the Sun
- Sensitive to both SI and SD DM, since they will both capture and annihilate
- Two different classifications of energy spectrum out:
    - Hard: W^+W^- or $\tau^+\tau^-$
    - Soft: $\mathbf{b\bar{b}}$

Dark Matter Annihilation



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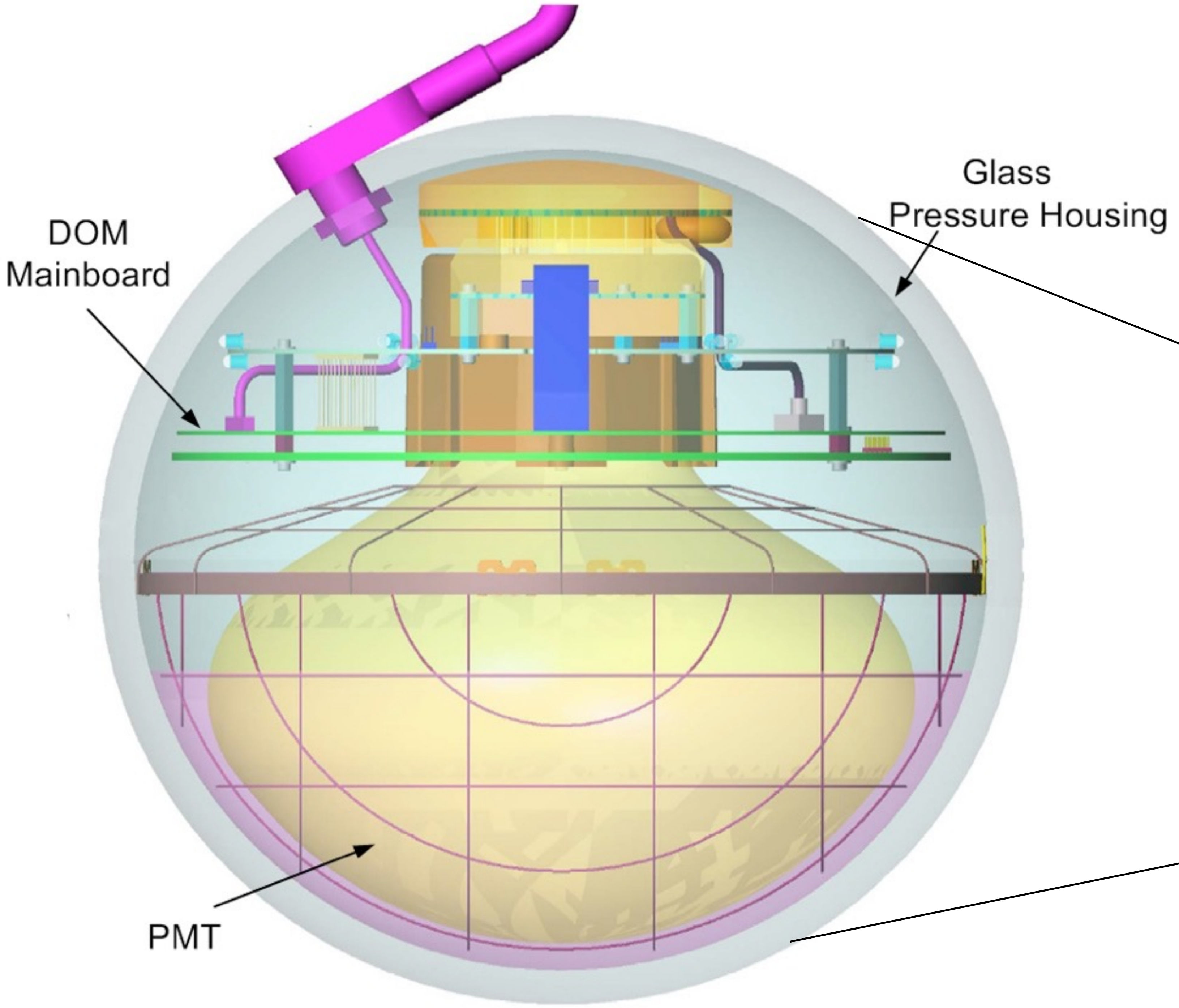
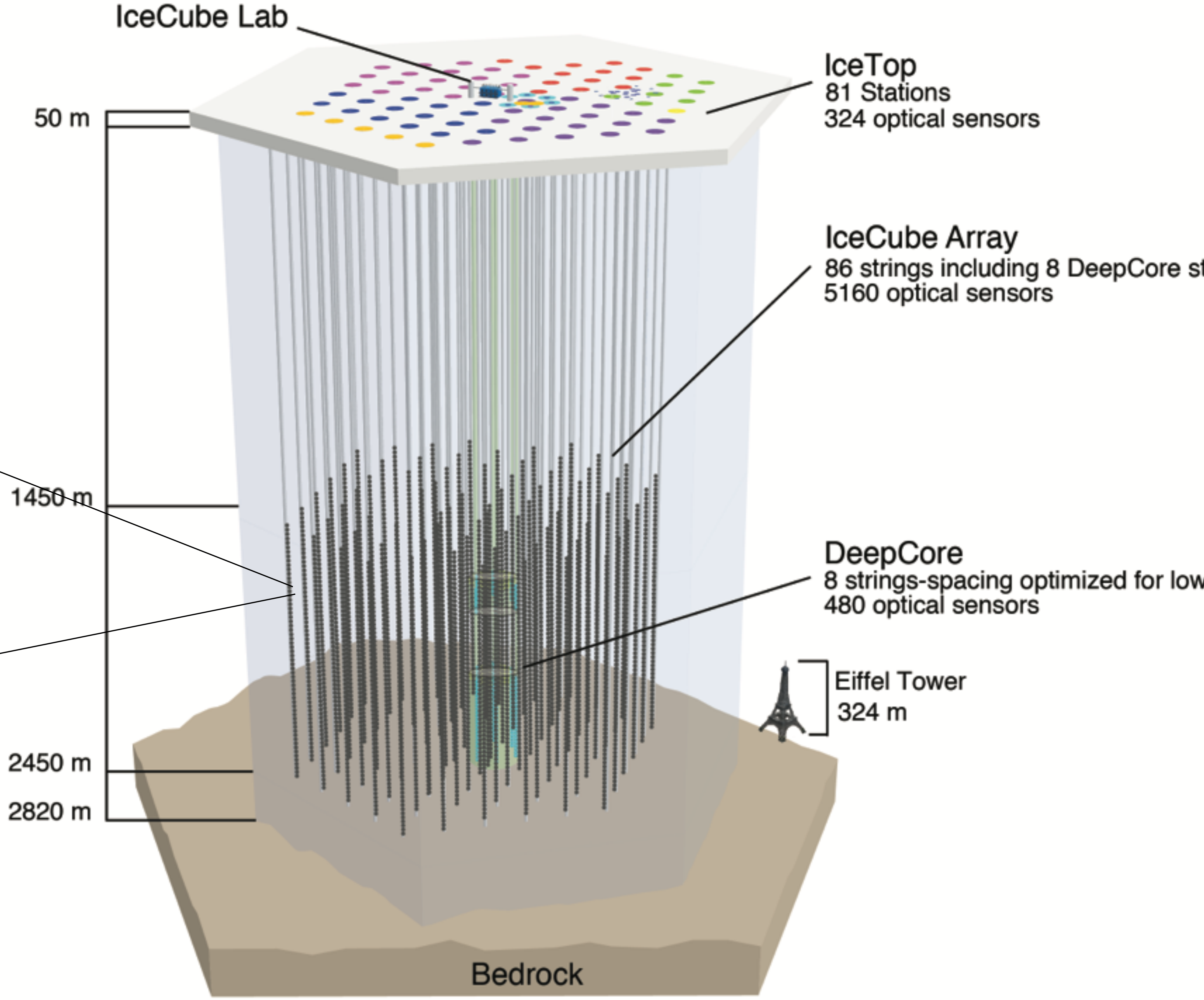
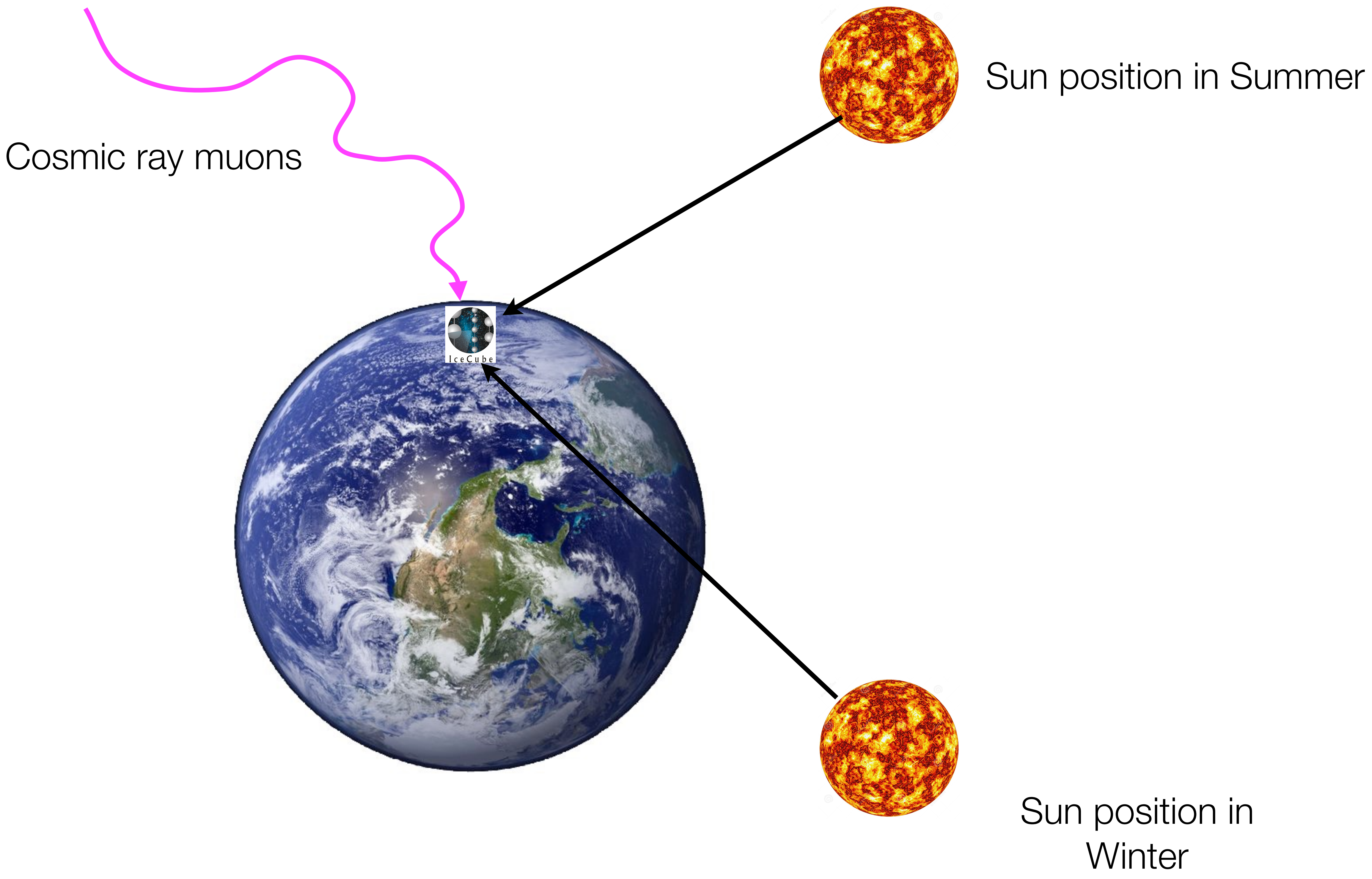
IceCube/DeepCore



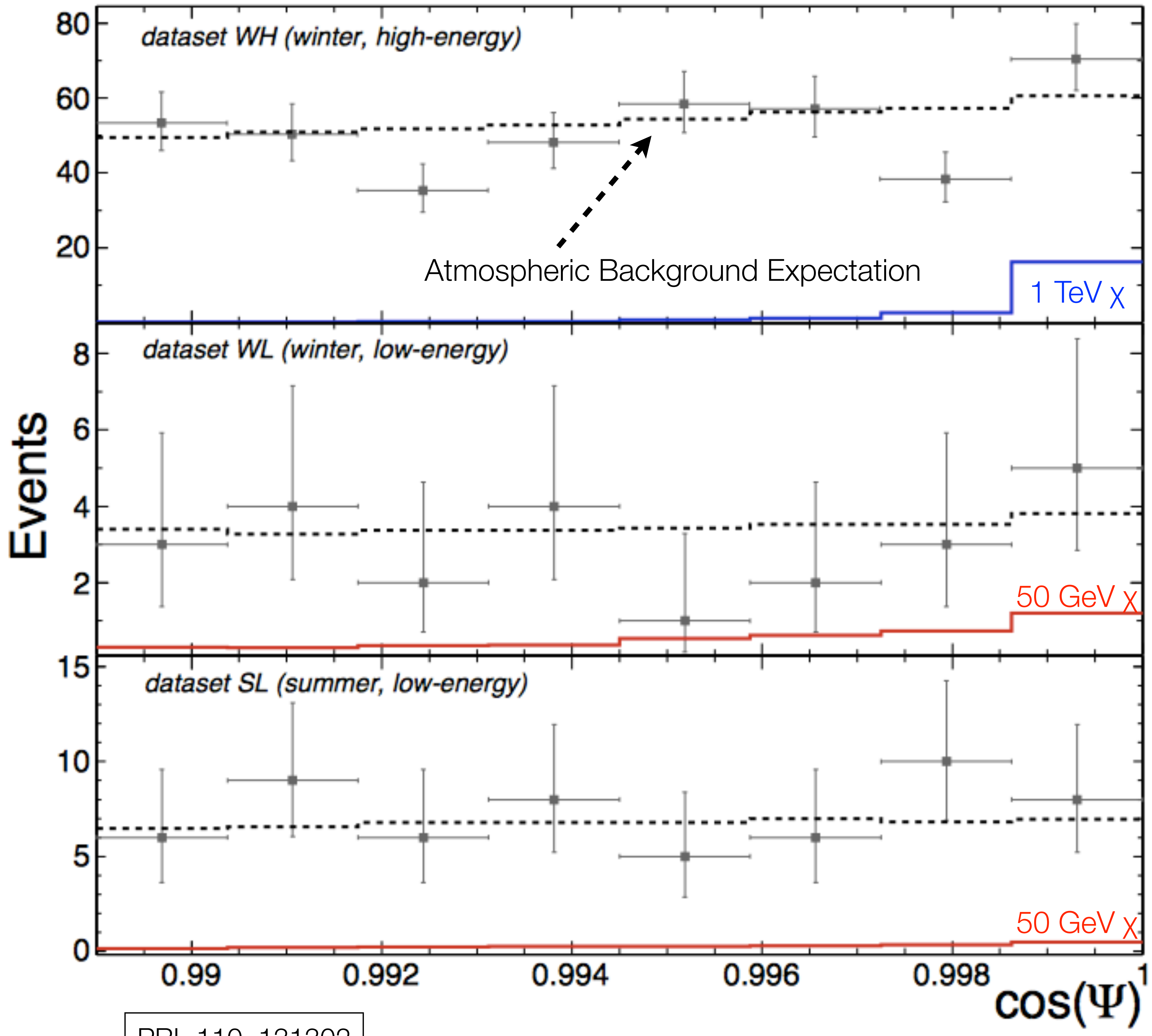


Studying Neutrinos from the Sun



Note: *dramatically* not to scale

Analysis

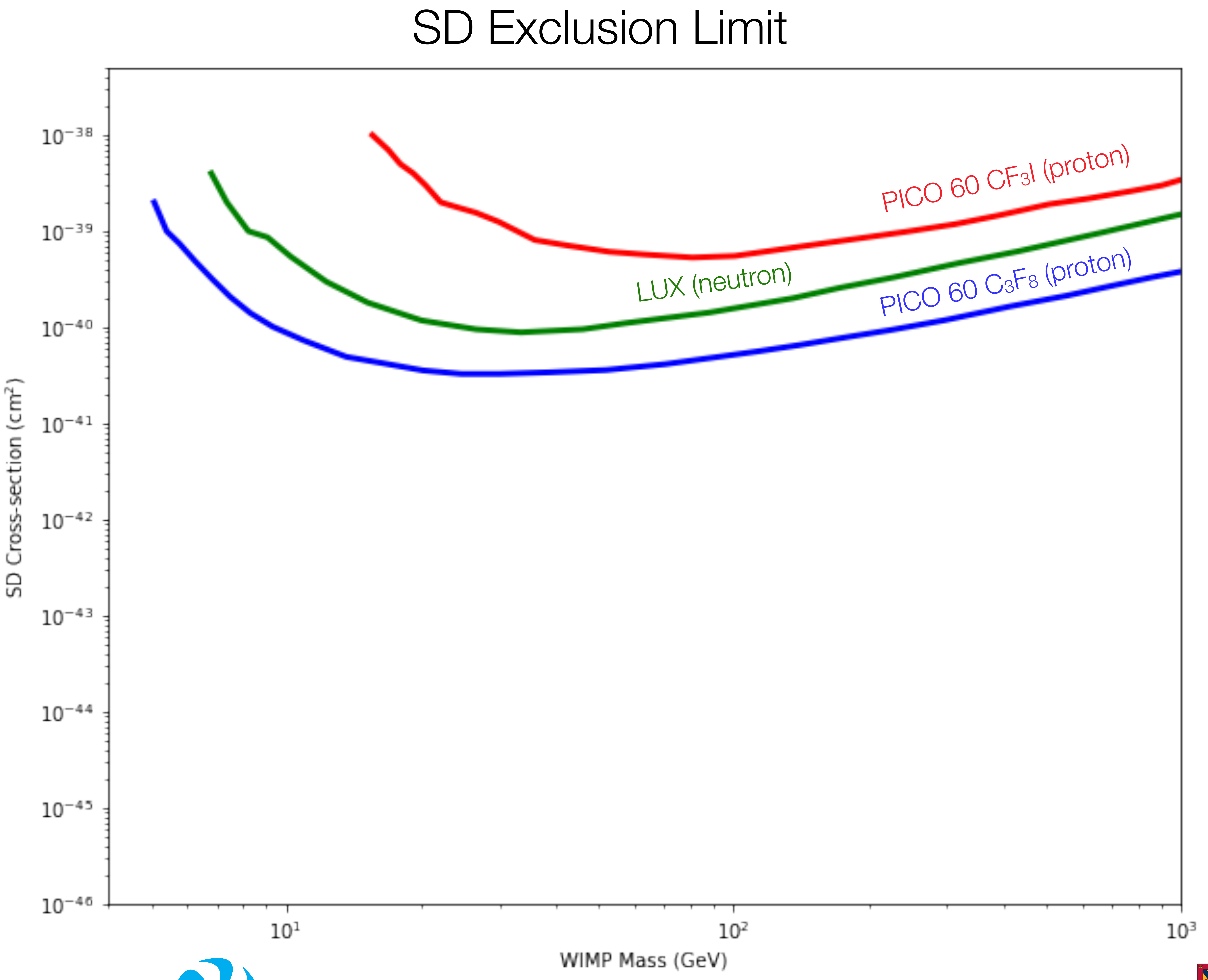


PRL 110, 131302

- No excess seen in the direction of the Sun
- A limit is placed on the capture rate and therefore the cross-section

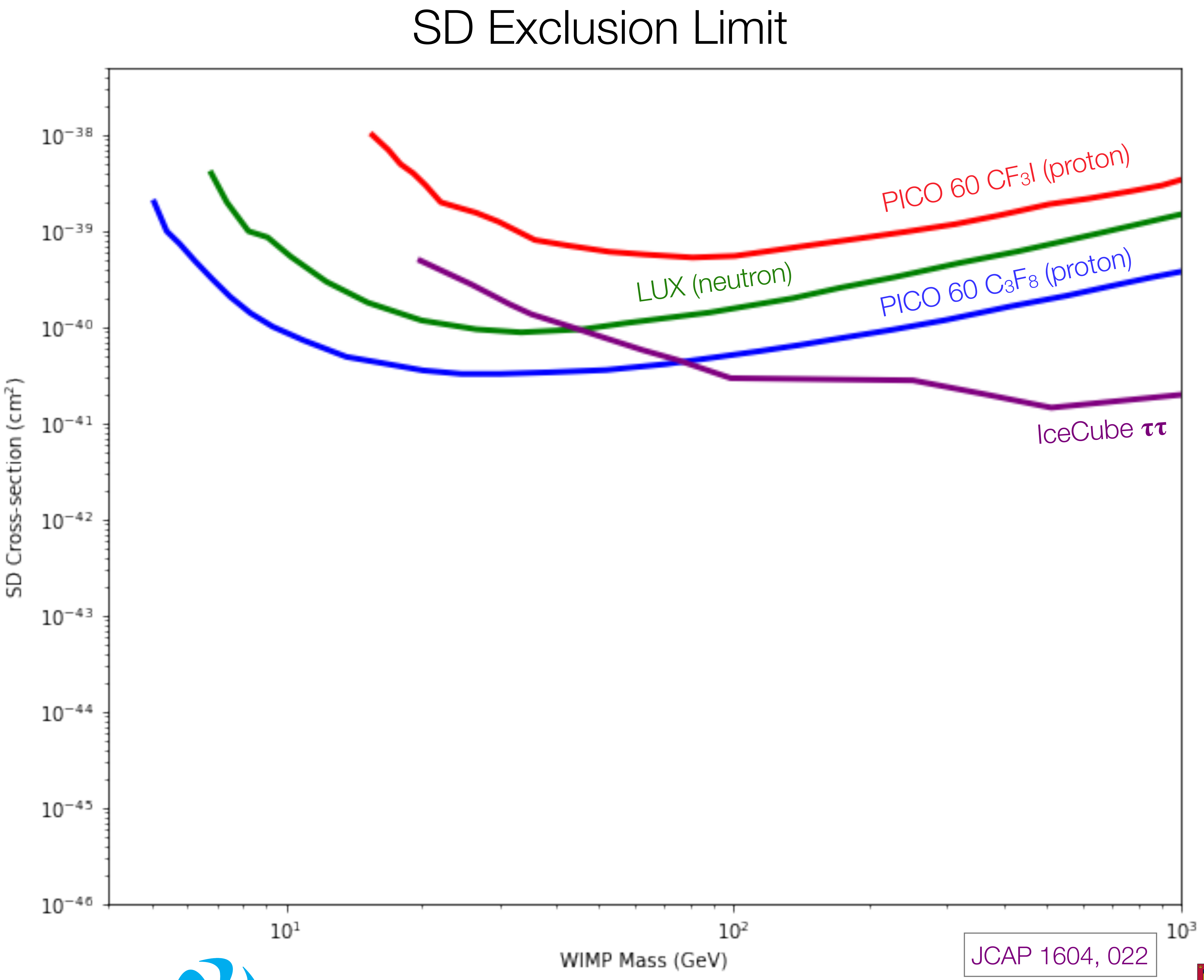
Limits

- Since the primary reaction is on Hydrogen, the majority of the sensitivity is in the SD sector
- This is a reminder of the state of the art in that limit



Limits

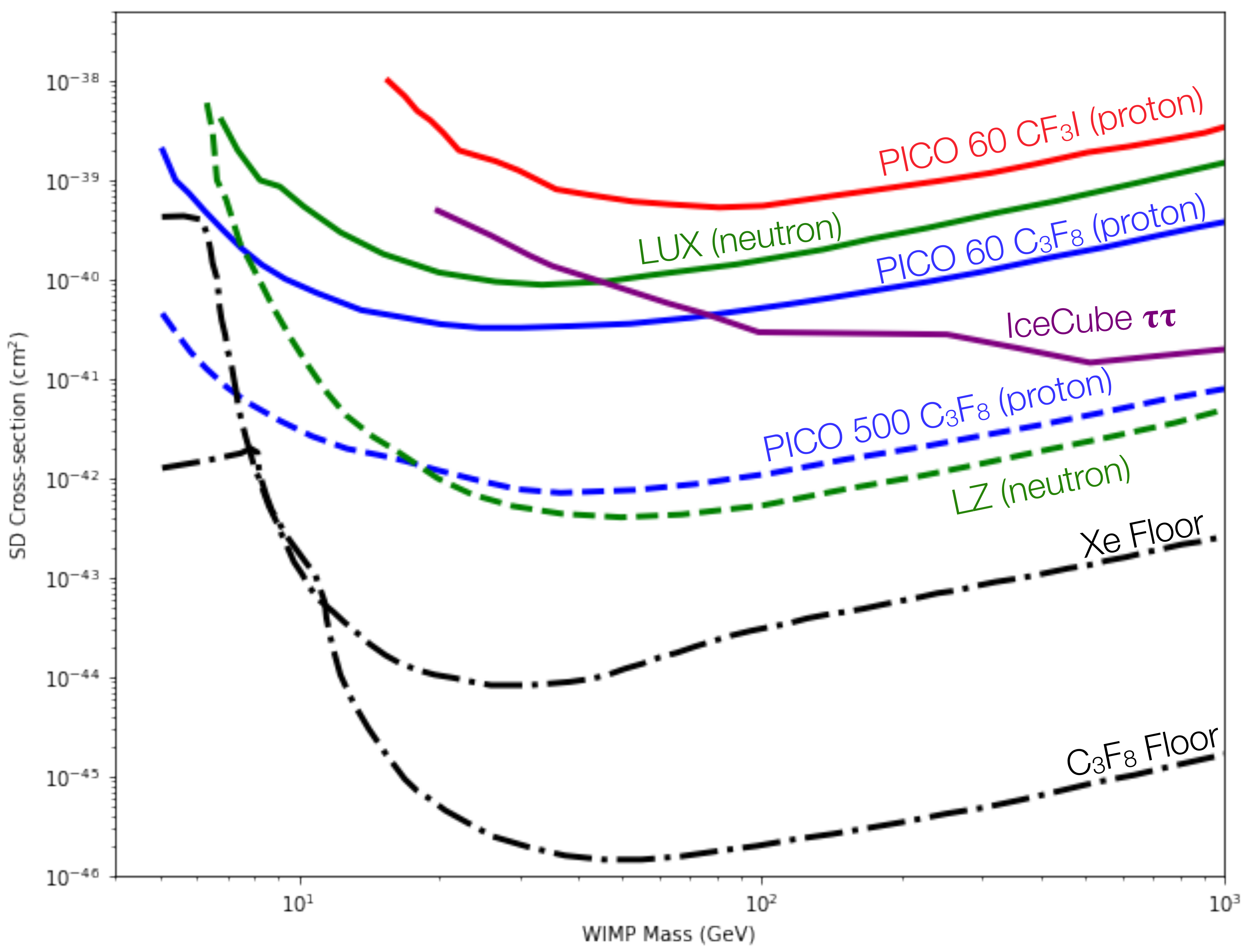
- Since the primary reaction is on Hydrogen, the majority of the sensitivity is in the SD sector
- The best limit from IceCube is into the $\boldsymbol{\tau\tau}$ channel



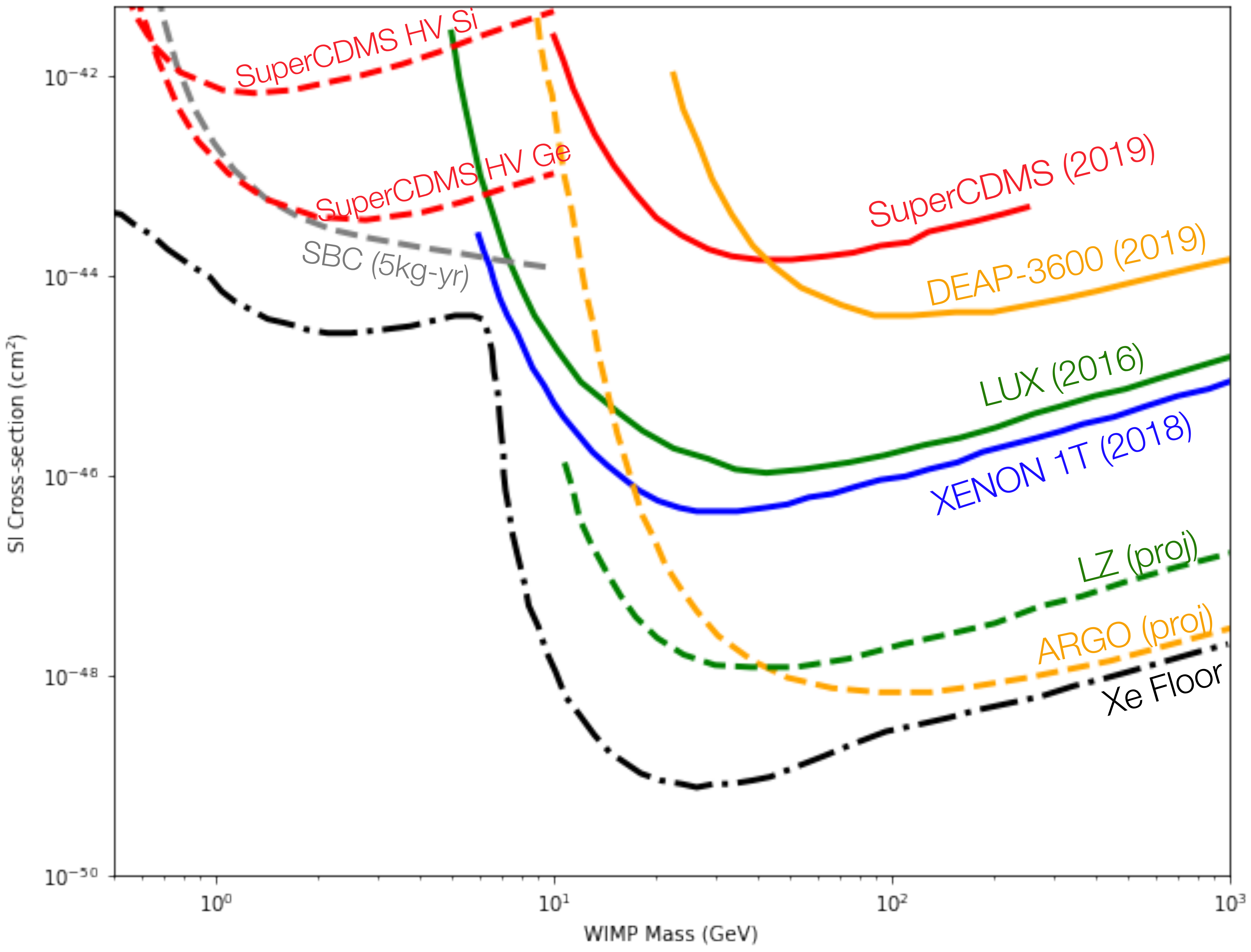
JCAP 1604, 022

Conclusions

SD Exclusion Limit



SI Exclusion Limit



- Rich field with much area left to explore
- Direct dark matter detectors have a shift in focus coming soon